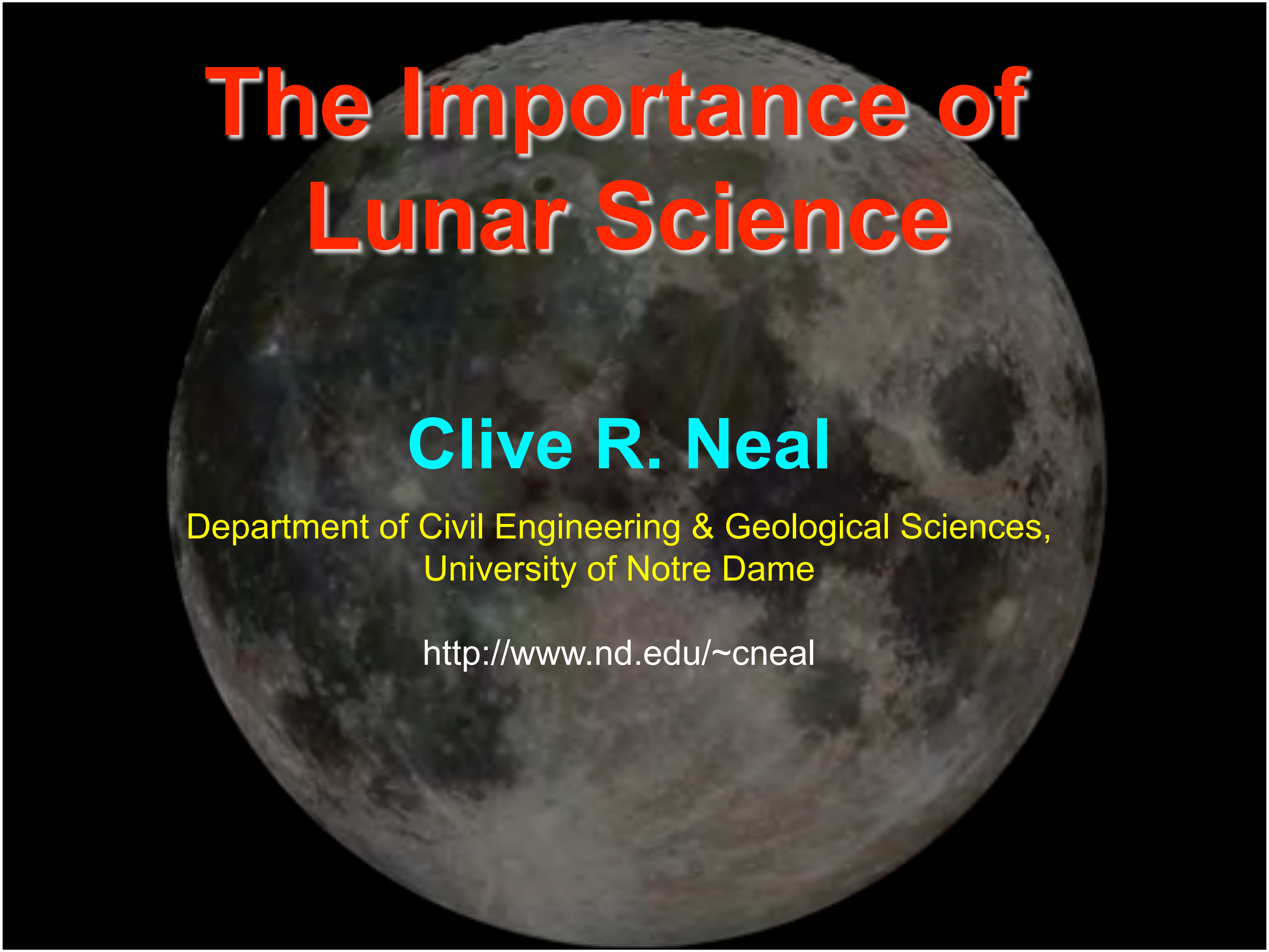
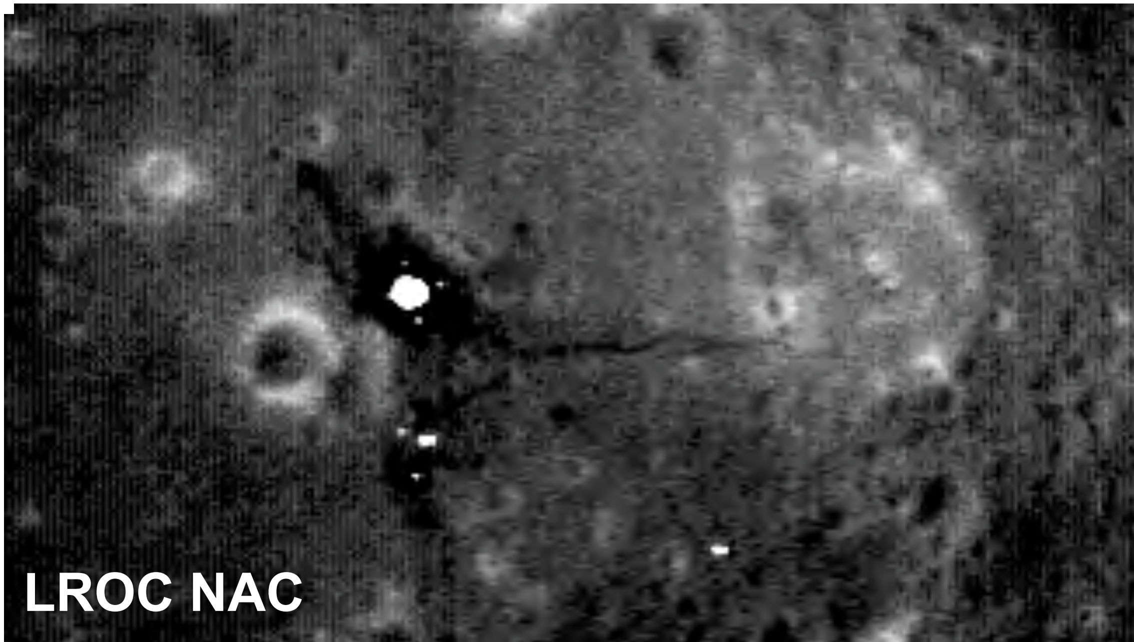
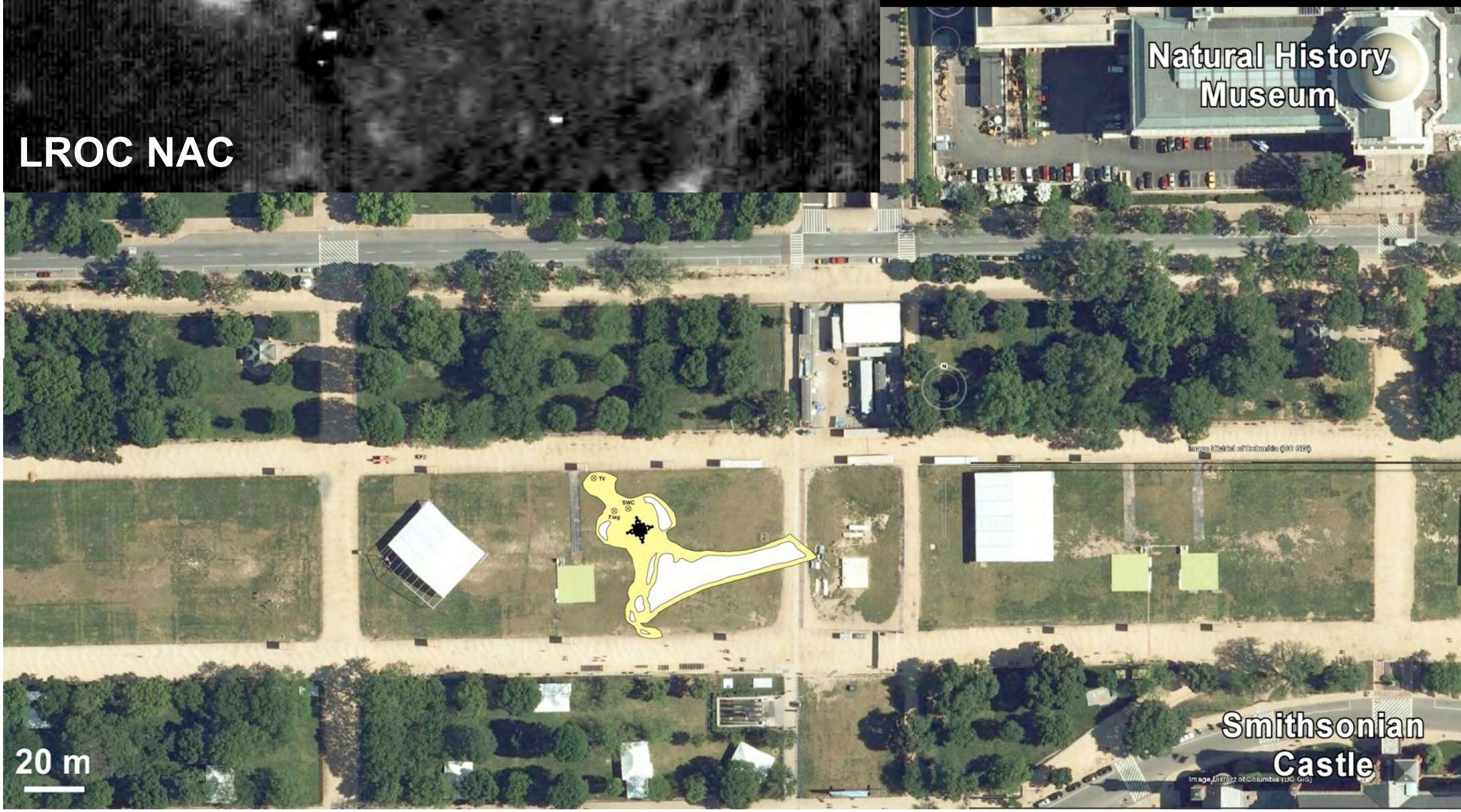
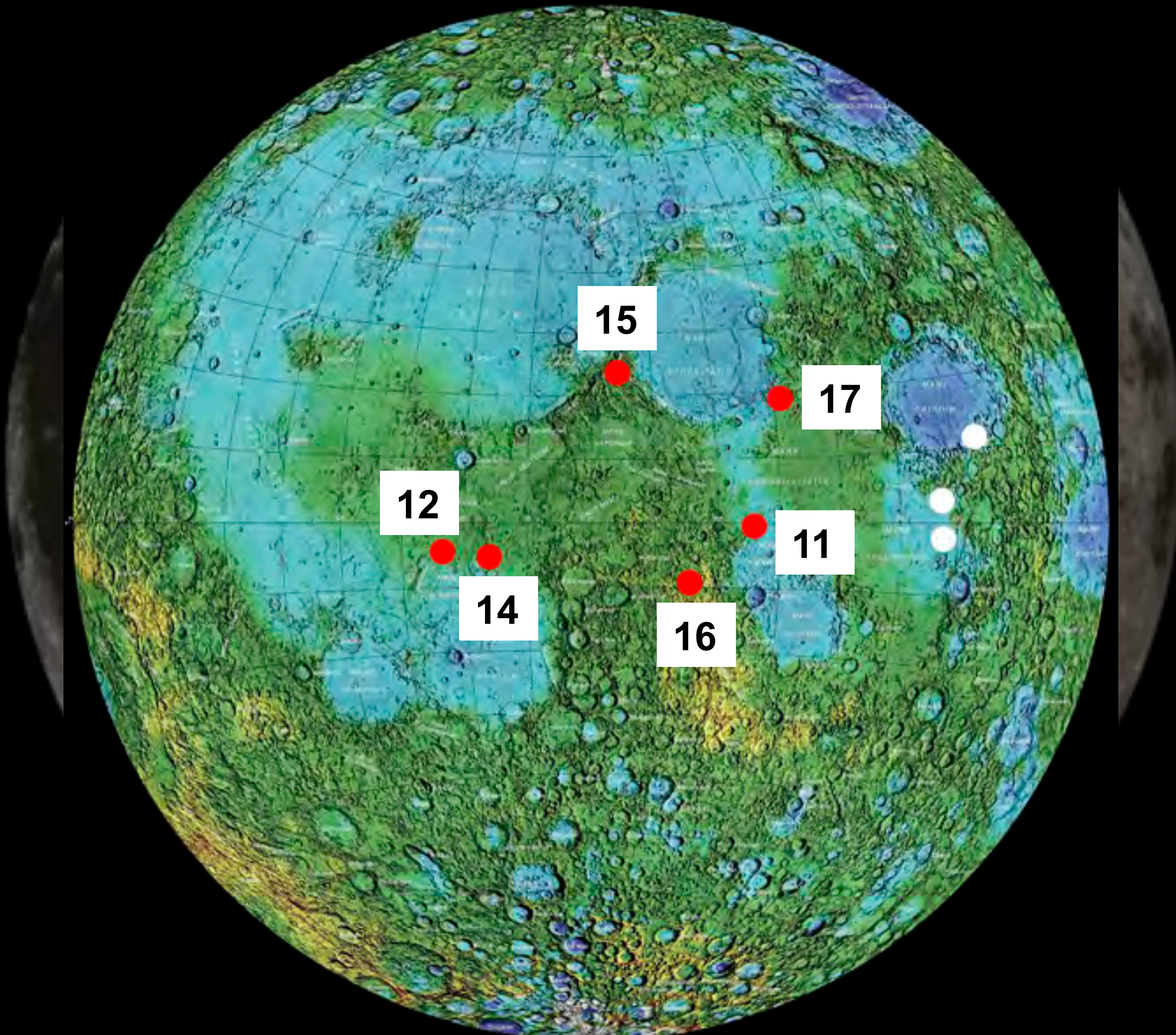

The Importance of
Lunar Science
Clive R. Neal
Department of Civil Engineering & Geological Sciences,
University of Notre Dame
http://www.nd.edu/~cneal

Apollo 11 on the National Mall

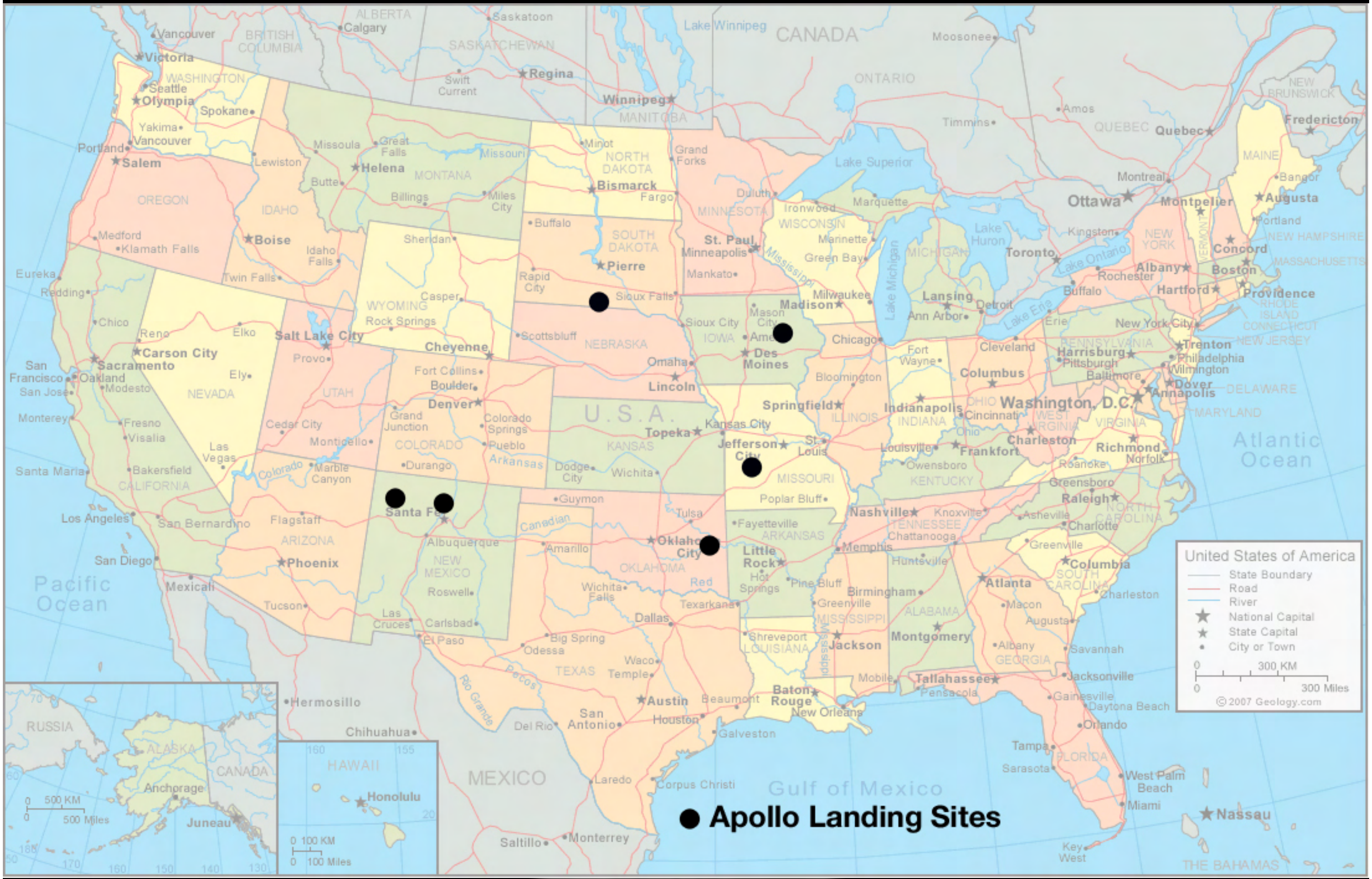




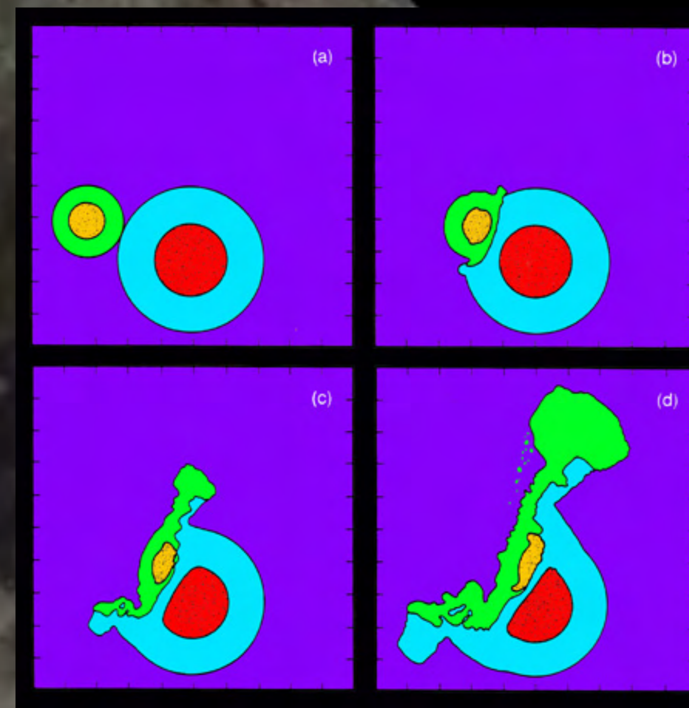
Apollo Landing Sites (1969-1972)



Apollo Exploration of the USA

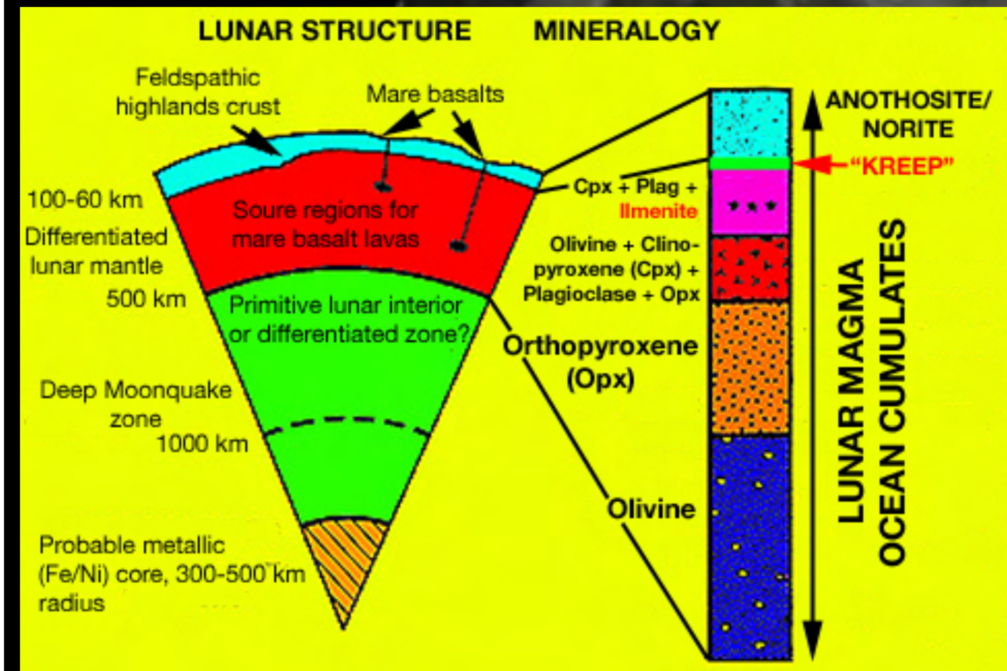


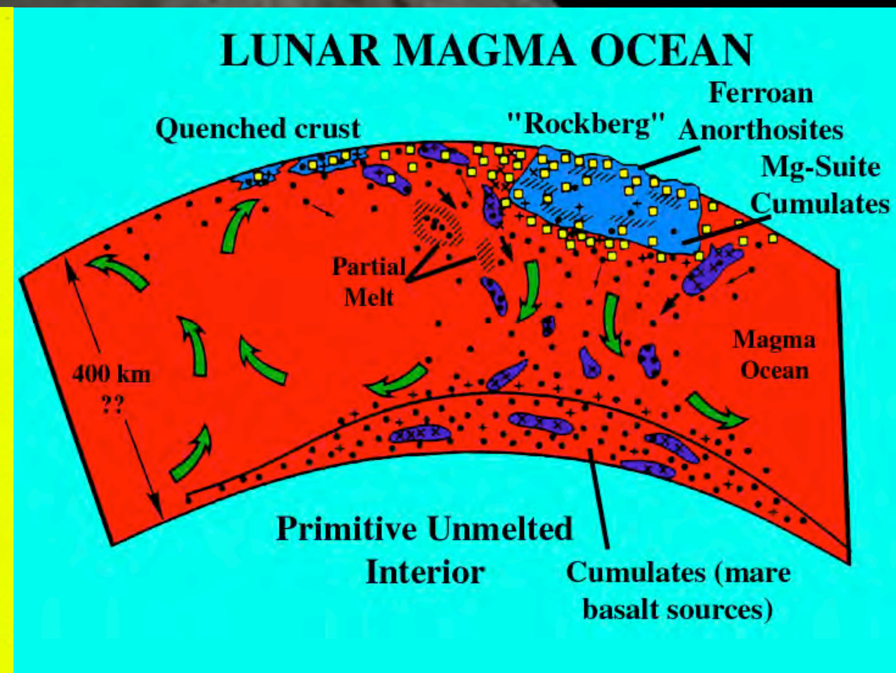
What do We Know about the Moon?



Moon is depleted in volatile elements and “core” elements

What do We Know about the Moon?



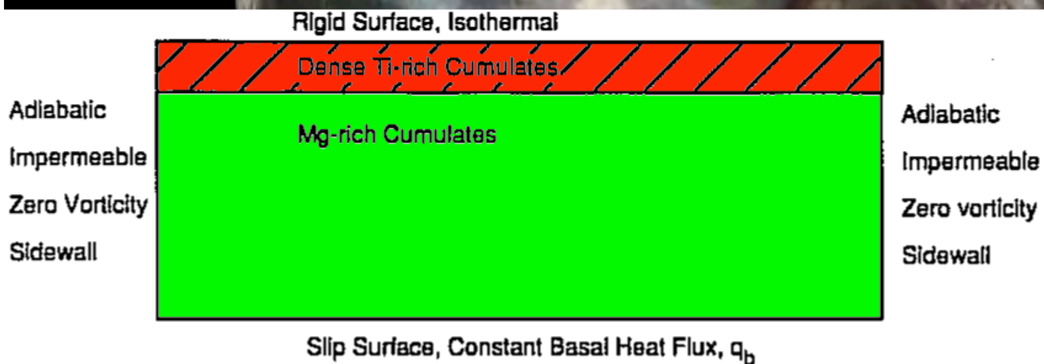


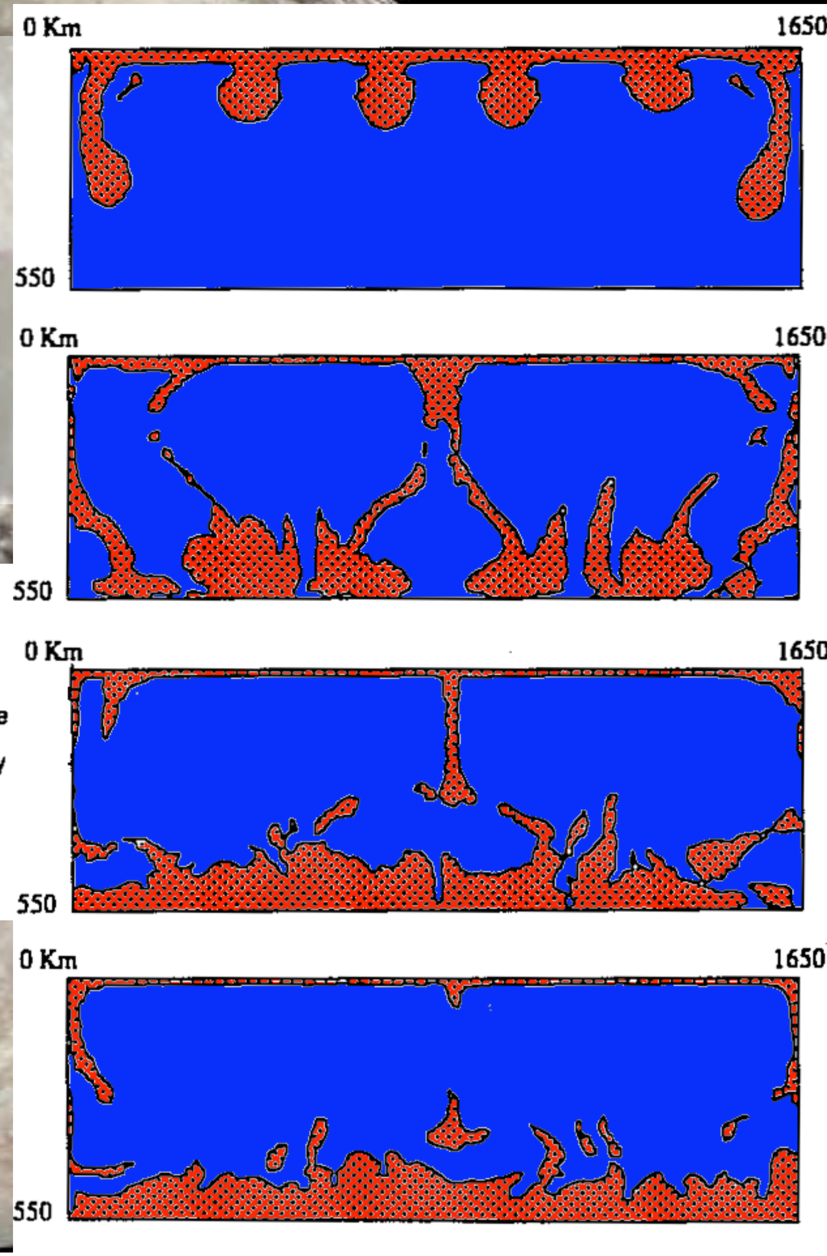
Differentiated source for basalts:
Olivine + Orthpyroxene early; Plagioclase, Clinopyroxene & **Ilmenite** later; "KREEP" = last dregs. Density instability.

Magma Ocean concept applied to Earth (e.g., McCulloch et al., 1986) and Mars (Elkins-Tanton et al., 2003).

Primer on Lunar Minerals

Olivine
Orthopyroxene (Opx)
Clinopyroxene (Cpx)
Plagioclase
Ilmenite





From Spera F.J. (1992) Lunar magma transport phenomena. *Geochimica et Cosmochimica Acta*, **56**, 2253-2265.

Samples from the Moon

Samples

Highlands (intrusive)

Ferroan Anorthosites (FANs)

Mg-Suite

Alkali Suite

Mare (extrusive)

Basalts

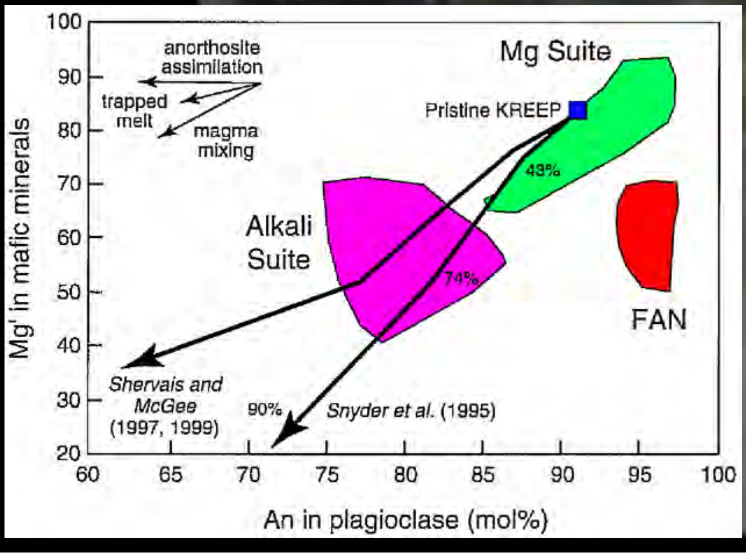
Glasses

Crystalline Basalts

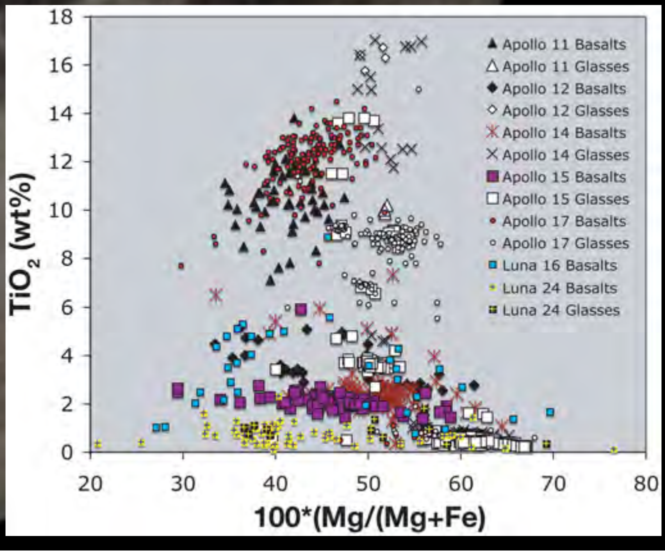
Very Low-Ti (VLT)

Low-Ti

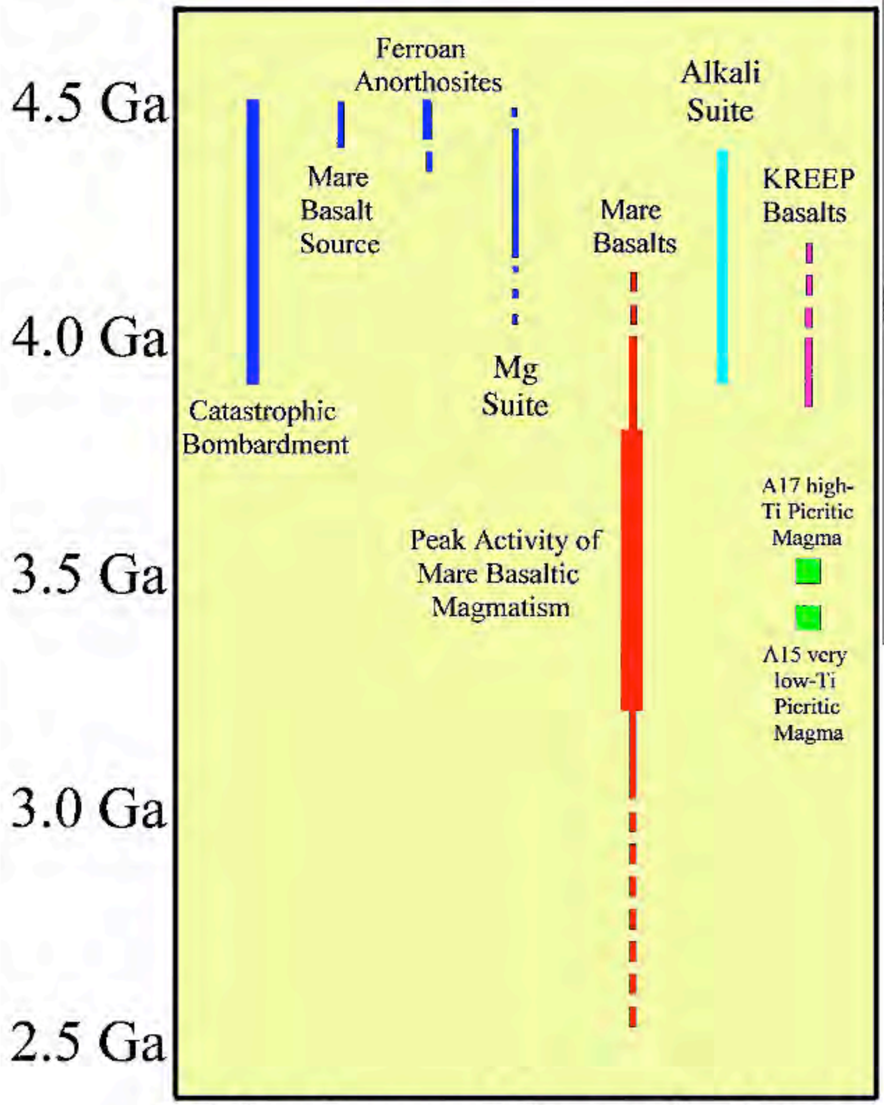
High-Ti



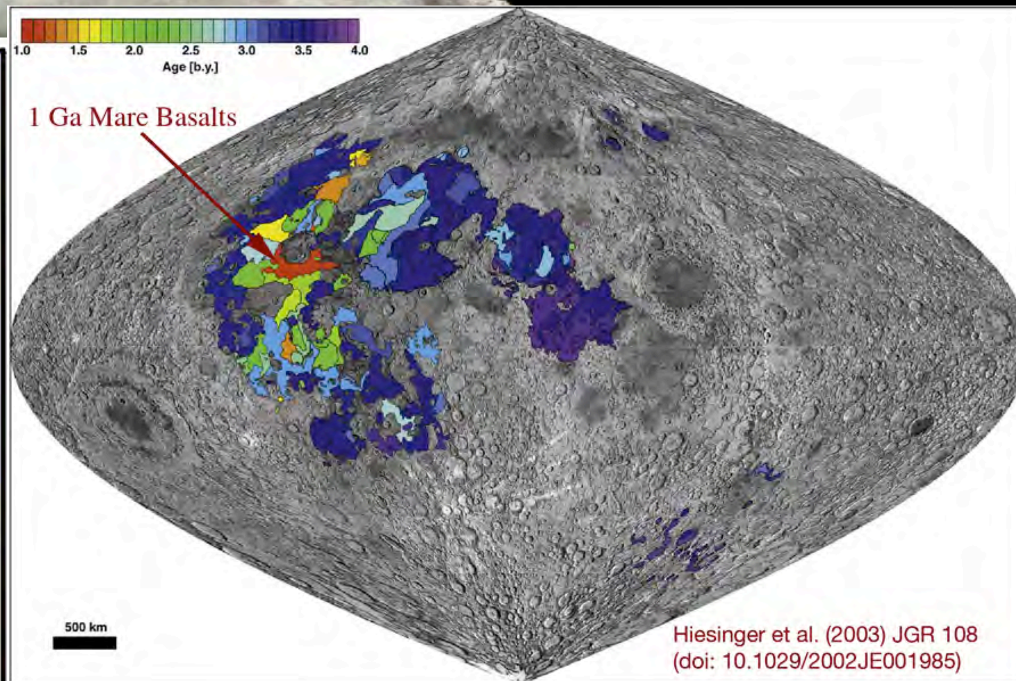
"KREEP"



Activity of the Moon



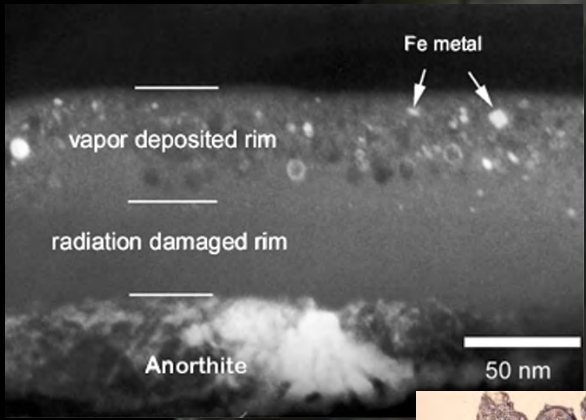
Major Lunar Magmatic Events

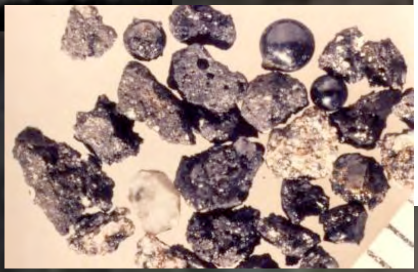


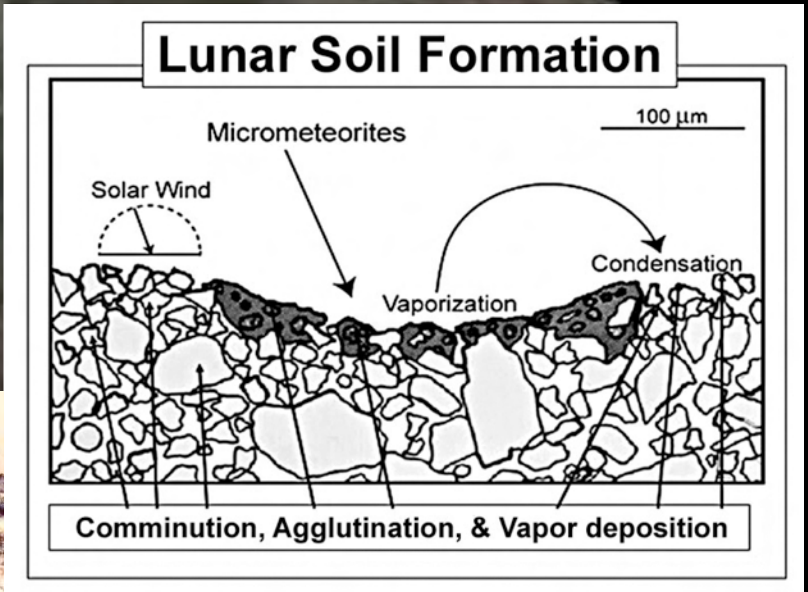
Hiesinger et al. (2003) JGR 108 (doi: 10.1029/2002JE001985)

Schultz, P. H., M. I. Staid, and C. M. Pieters (2006) Lunar activity from recent gas release. *Nature*, v. 444, p. 184-186.

What Do We "Know" About the Lunar Surface?







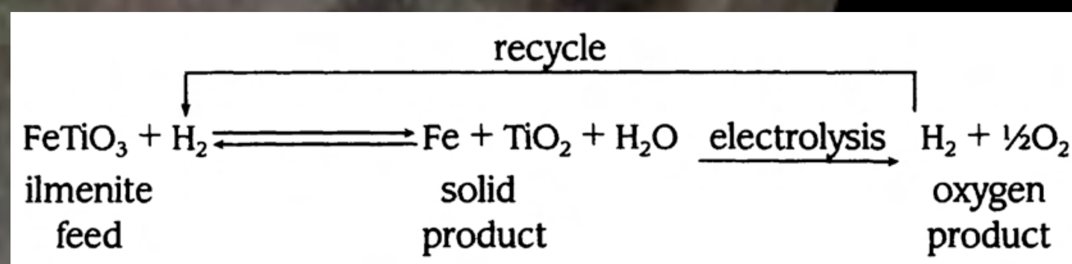
Agglutinates form through radiation and meteorite bombardment.

Forms Fe metal - produces spectral reddening in "mature" surfaces.

What Do We "Know" About the Lunar Surface?

Unhappy Moon!

Fe metal formed by an important "reaction".



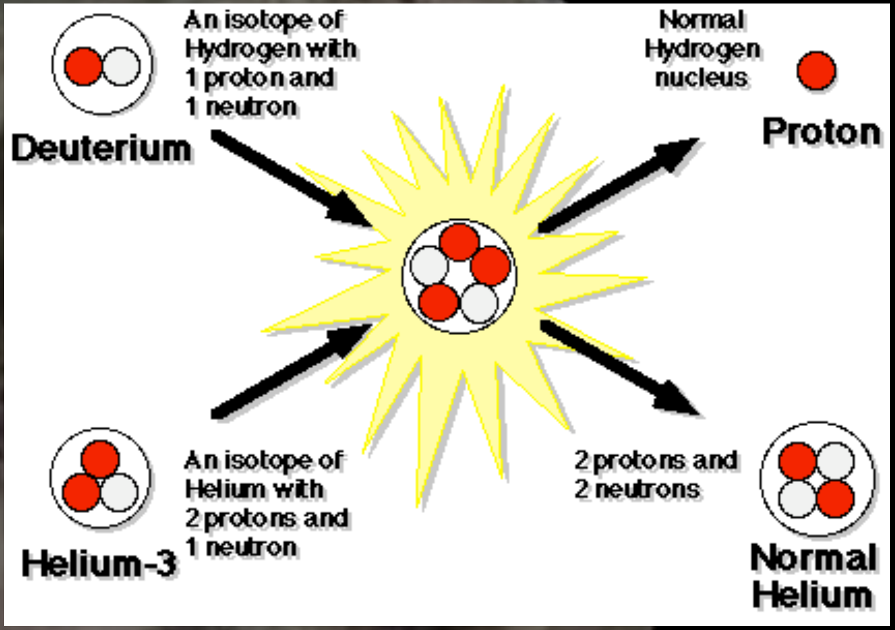
Living off the land! Water and Oxygen can be mined.

Why Should We Go Back to the Moon?

Helium-3

$$D + {}^{3}He \longrightarrow p(14.7\ MeV) + {}^{4}He\ (3.7\ MeV) + 18.4\ MeV$$

Nuclear fusion of ^{3}He produces no radioactive waste and (theoretically) a lot of energy!



About 25 tonnes of ^{3}He would power the United States for 1 year at our current rate of energy consumption.

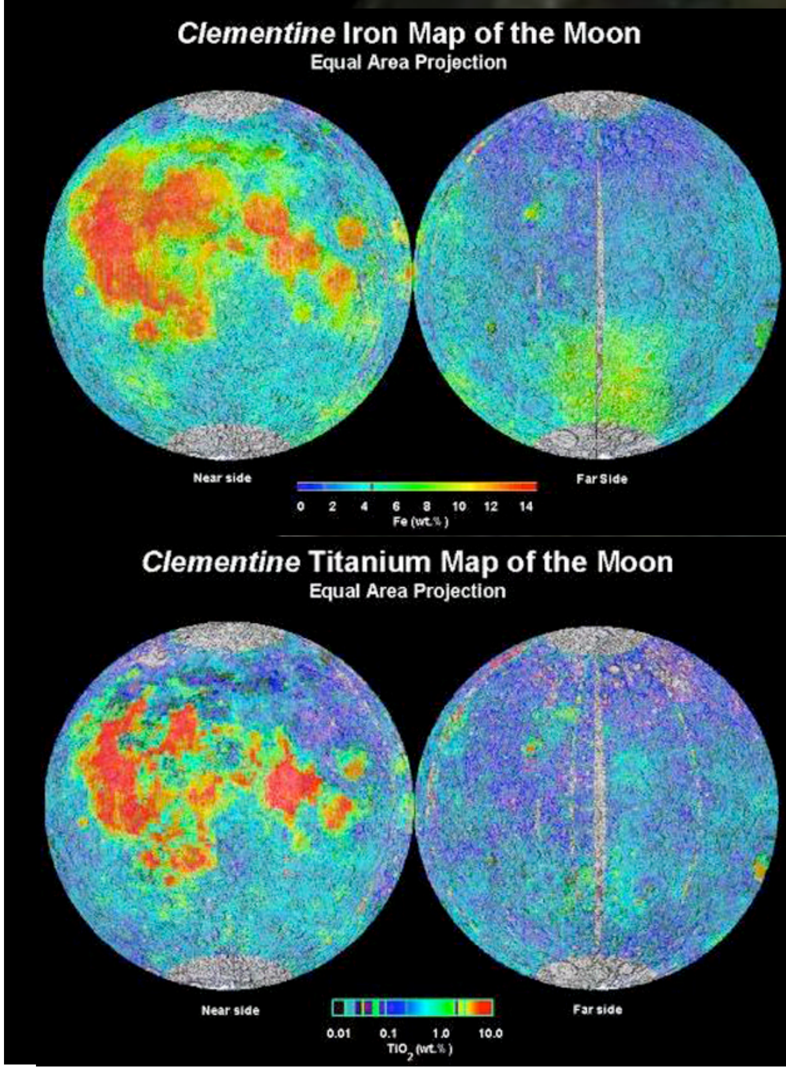
Perspective: that's about the weight of a fully loaded railroad box car, or a maximum Space Shuttle payload.

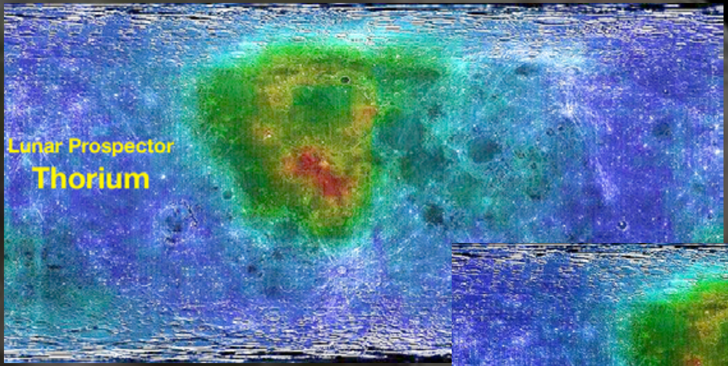
As a replacement for that fuel, that 25-tonne load of ^{3}He would worth on the order of \$75 billion today, or \$3 billion per tonne.

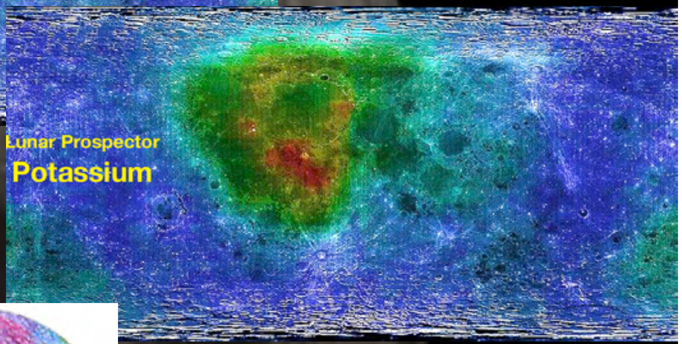
Sample data give estimates of ^{3}He on the Moon to be >1 million tonnes.

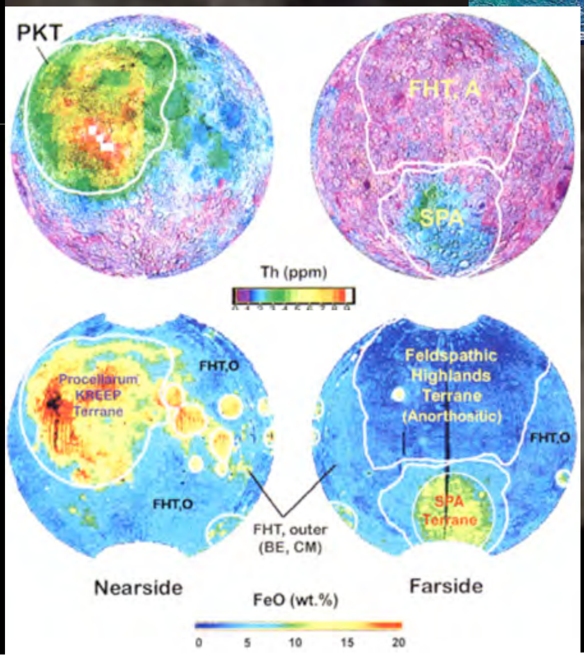
What Do We "Know" About the Lunar Surface?

Global Element Maps





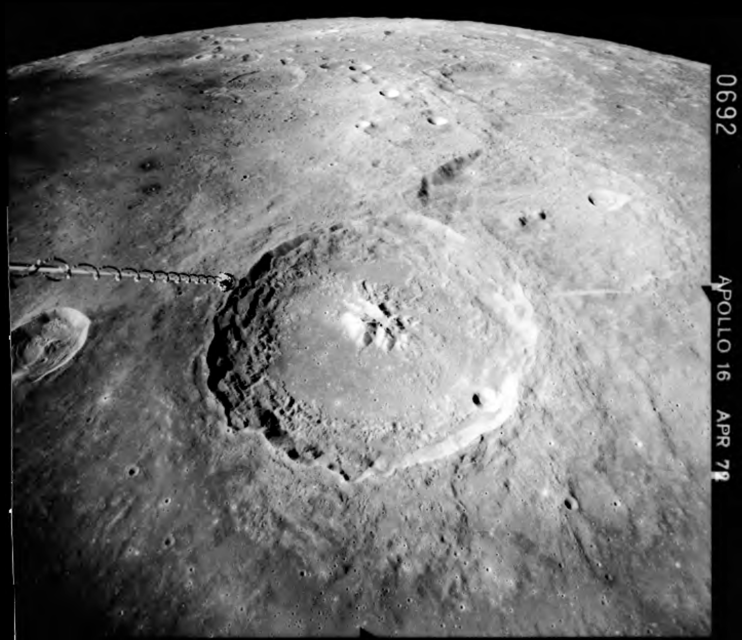


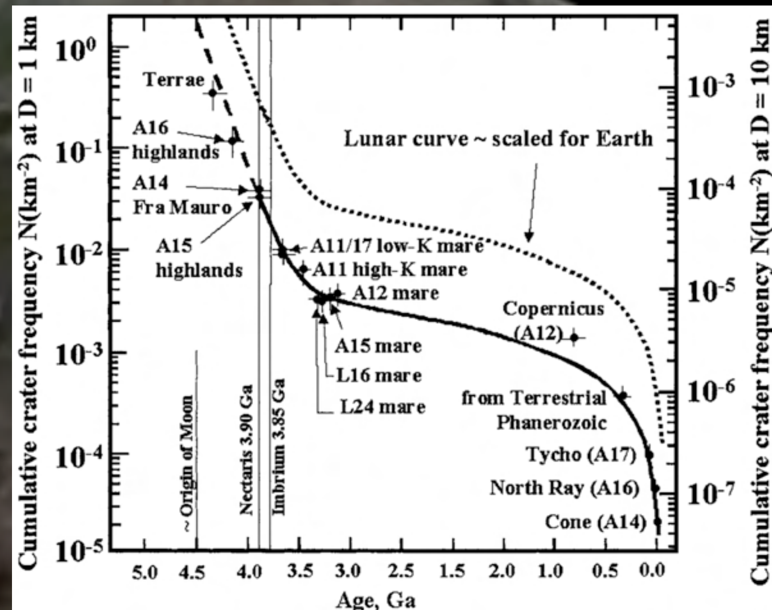


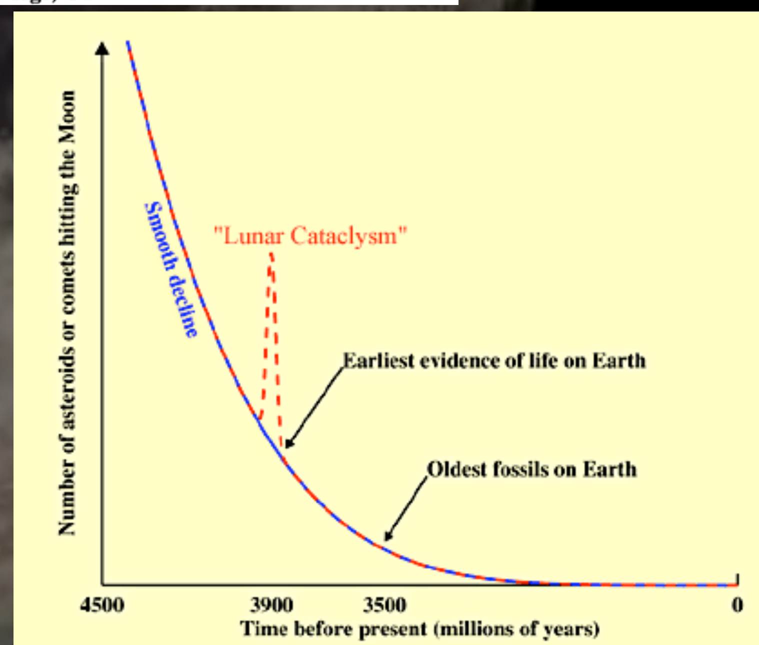
[B. Jolliff et al. (2000) *JGR* **105**, 4197]

Terrane Boundaries.

Impact Chronology



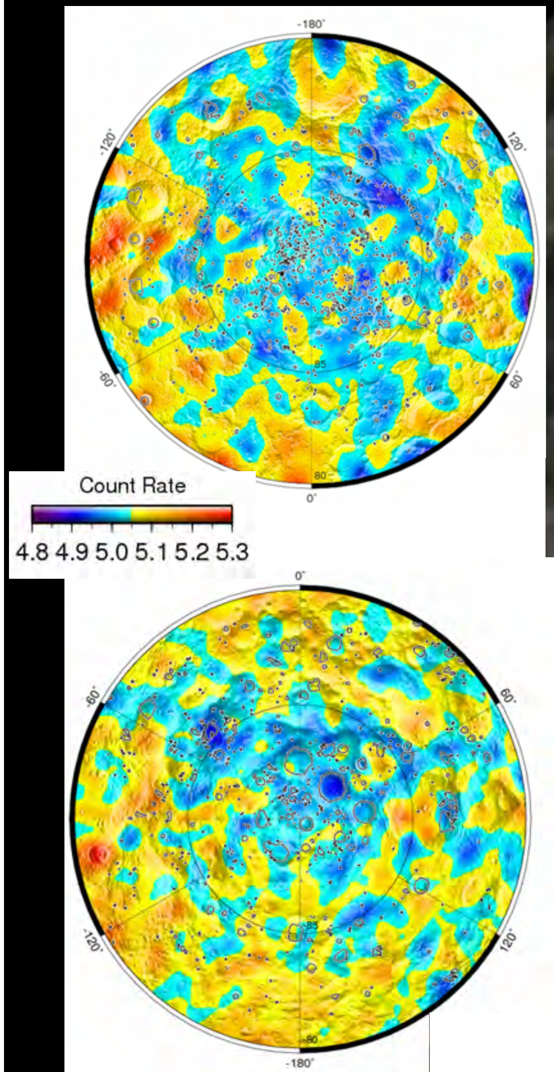




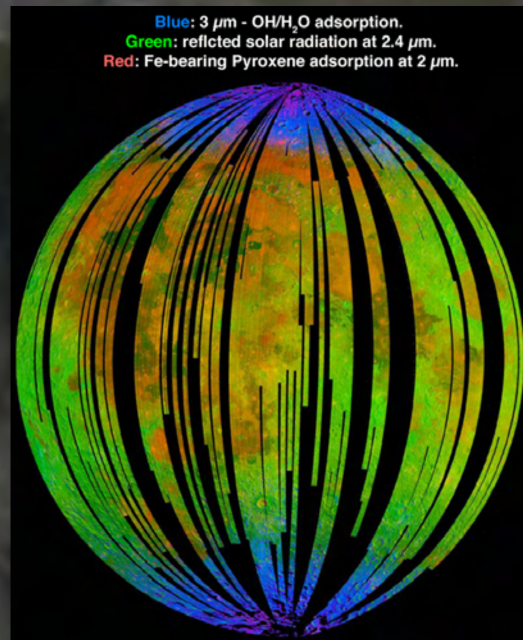
(Courtesy of B. A. Cohen)

Recent Mission Results

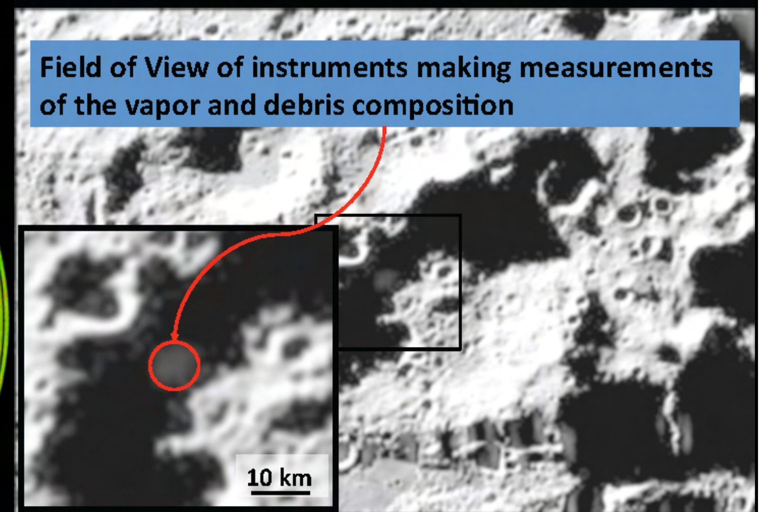
Exogenous Volatiles on the Moon



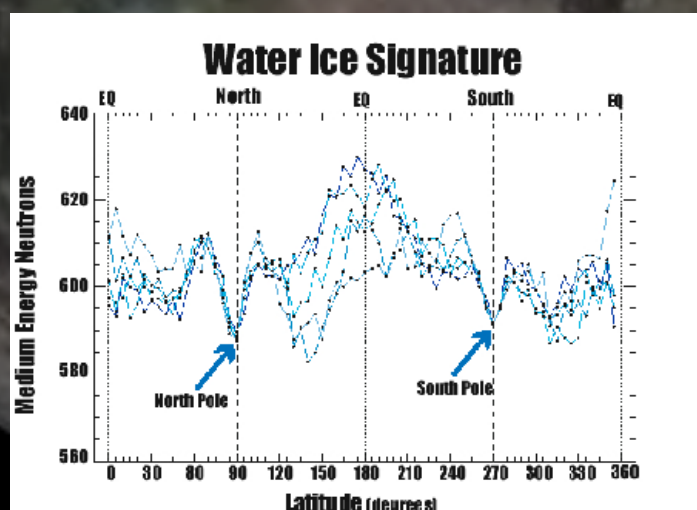
Hydrogen Deposits: LRO



LCROSS Visible Camera Image of Ejecta Cloud



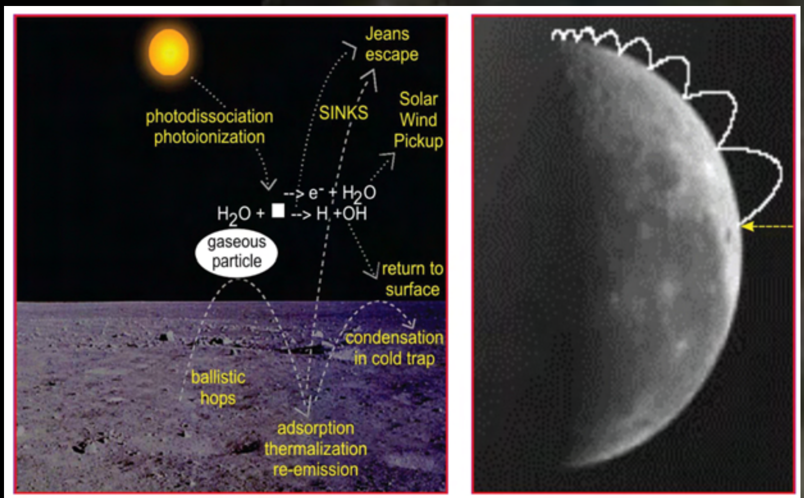
Volatile Deposits: Chandrayaan-1, LCROSS/LRO

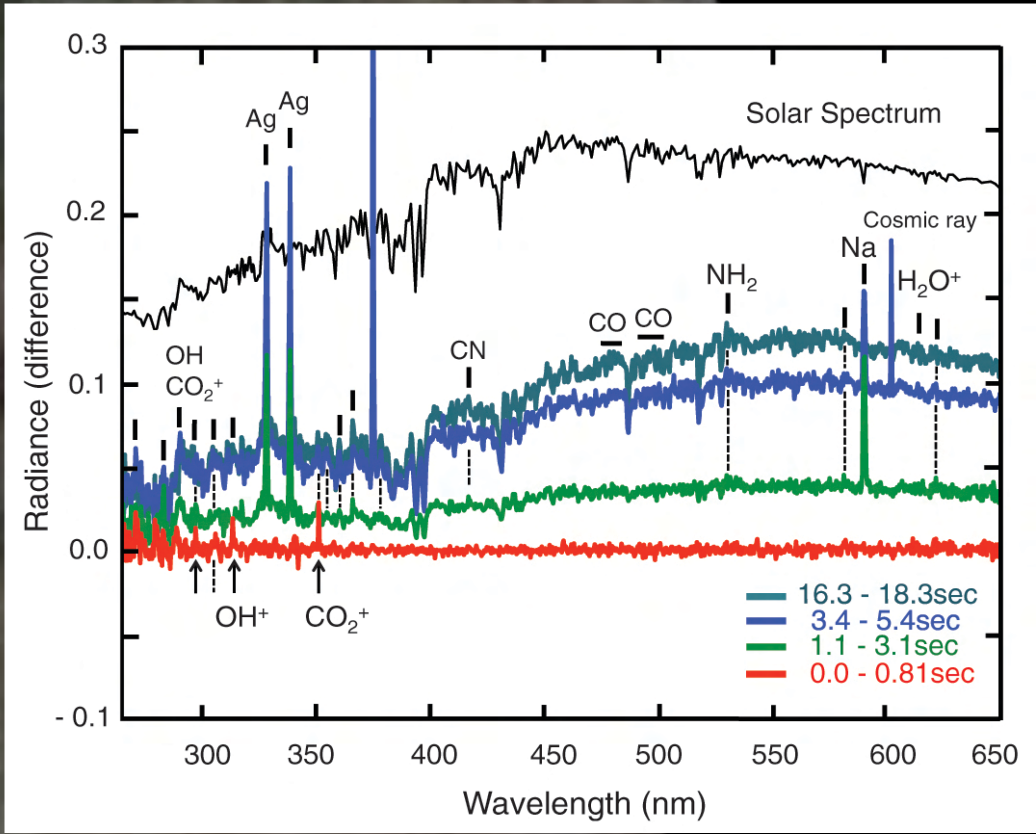


Hydrogen Deposits: Lunar Prospector

Recent Mission Results

Exogenous/Endogenous Volatiles on the Moon?





Recent Mission Results

Old Paradigm, new planet:

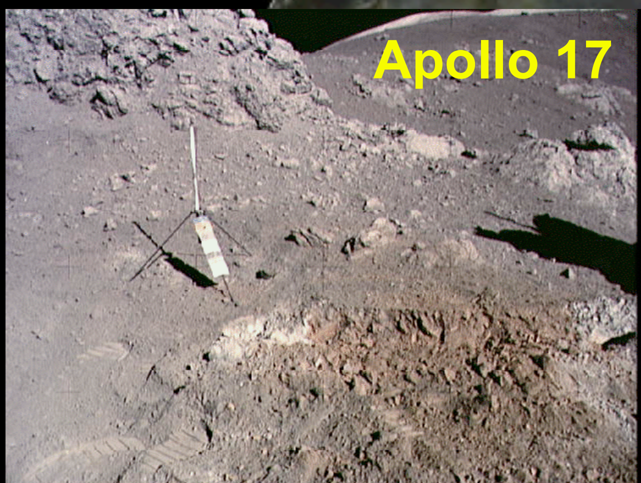
"We've found water on ~~Mars~~ the Moon – again!!"

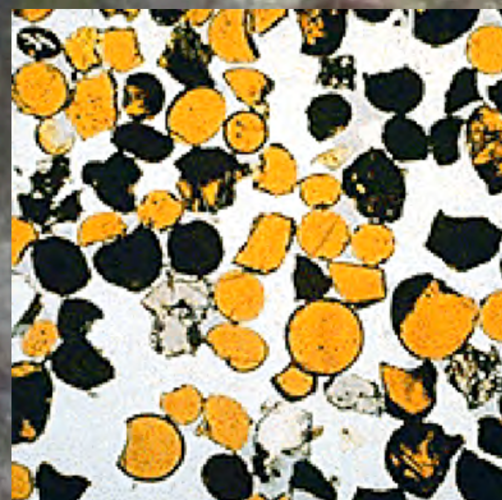
Information on the Interior of the Moon

Very little of the lunar surface was sampled.

No direct sampling of the lunar mantle (no mantle xenoliths).

Difficult to identify a primary melt (glasses are the best bet!)





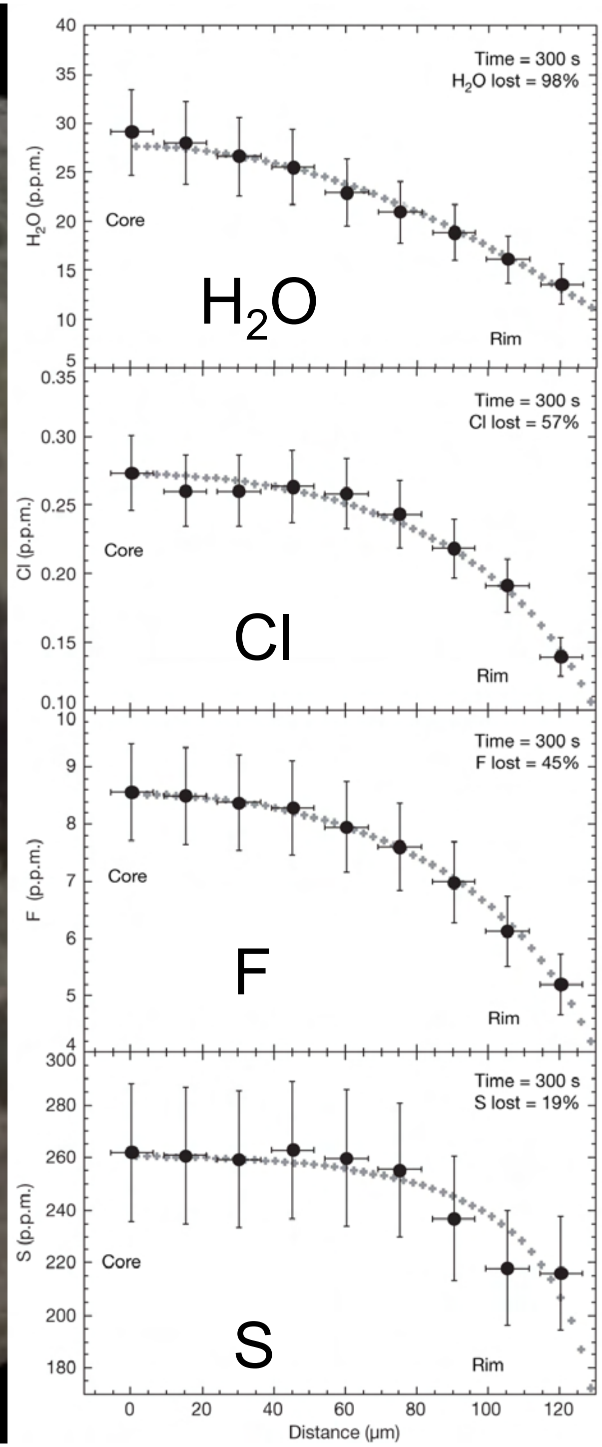
Volcanic glass beads from fire fountaining.
Distinct from crystalline mare basalts.
Source Regions: Mare basalts = 100-250 km;
Glasses = 360-520 km.

Endogenous Volatiles

Saal et al. (2008
Nature 454, 192-195)

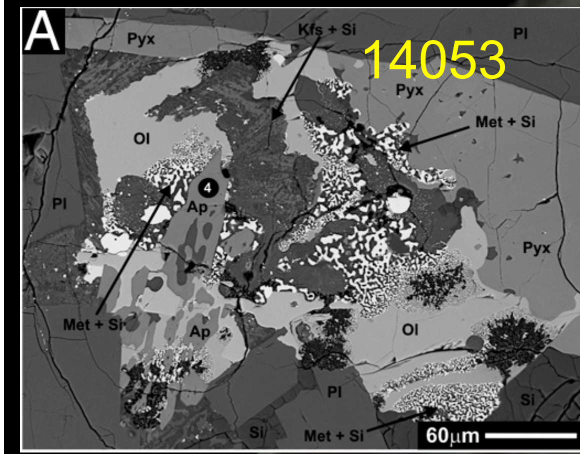
Apollo 15 Green Glass (VLT)

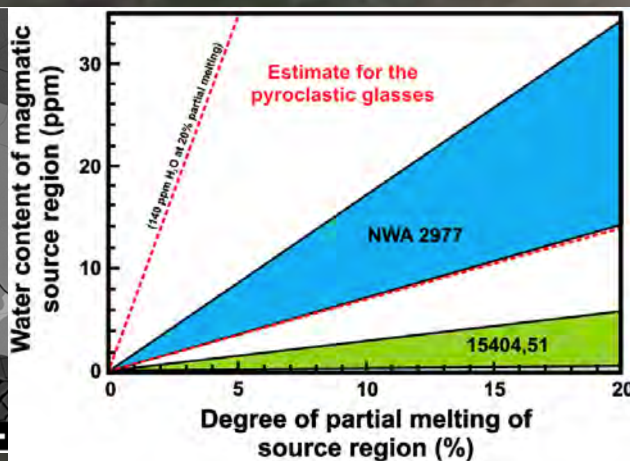
Water in the Glass Parent Magma:
260-745 ppm



Endogenous Volatiles

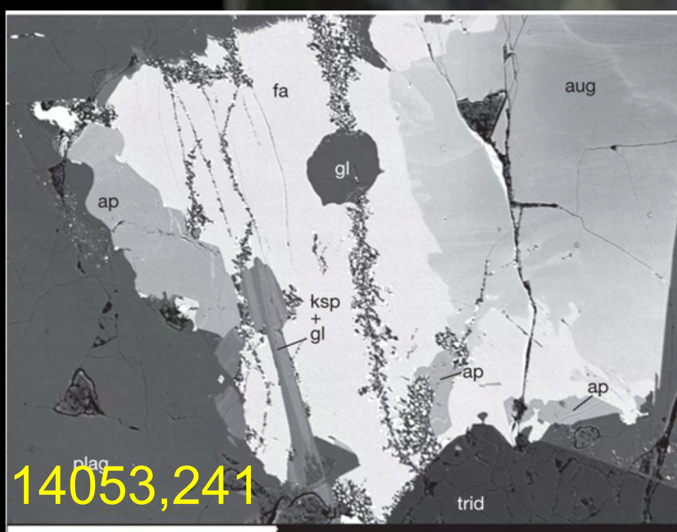
OH content of phosphates





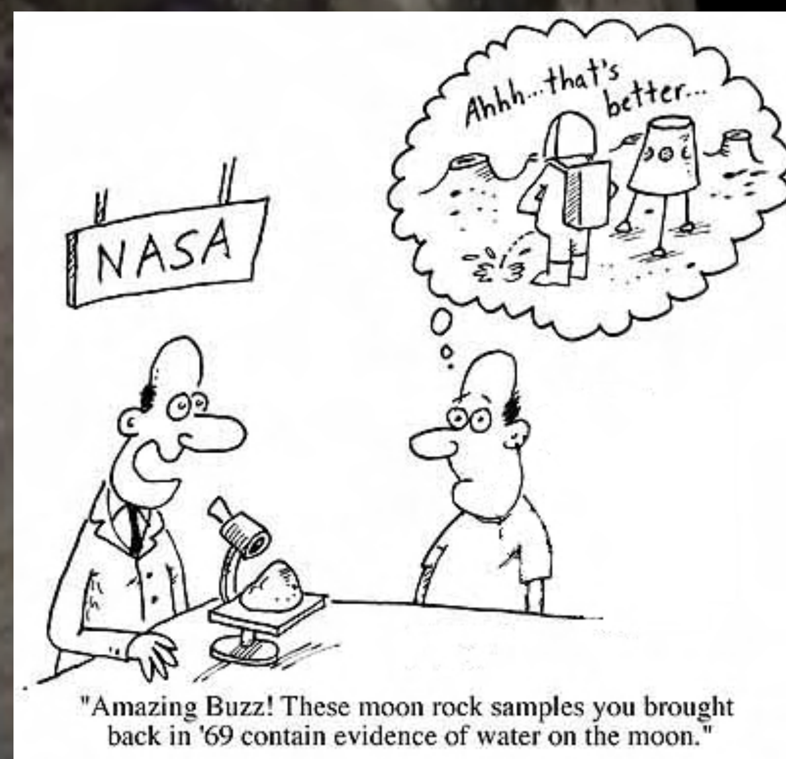
McCubbin et al. (2010) Proc. Nat. Acad. Sci. 107, 11223-11228.

Water in Mare Basalt Sources: 2-5 ppm

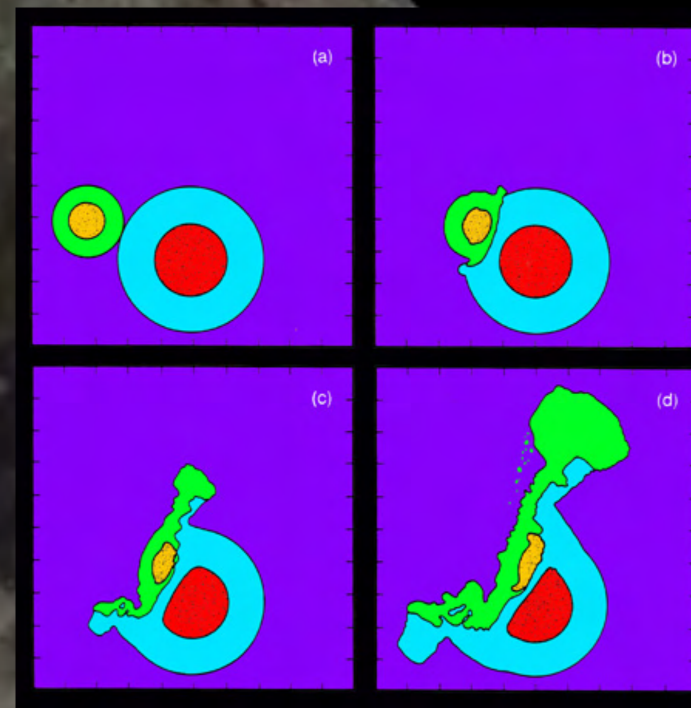


Liu et al. (2010) LPSC 41

Boyce et al. (2010) Nature 466, 466-469



What do We Know about the Moon?

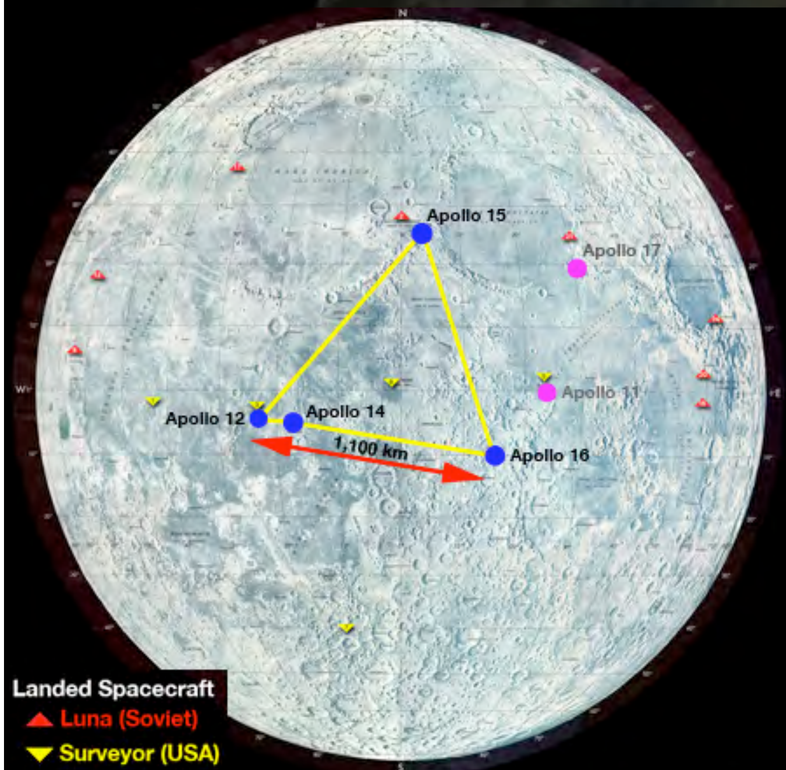


Moon is depleted in volatile elements and “core” elements?

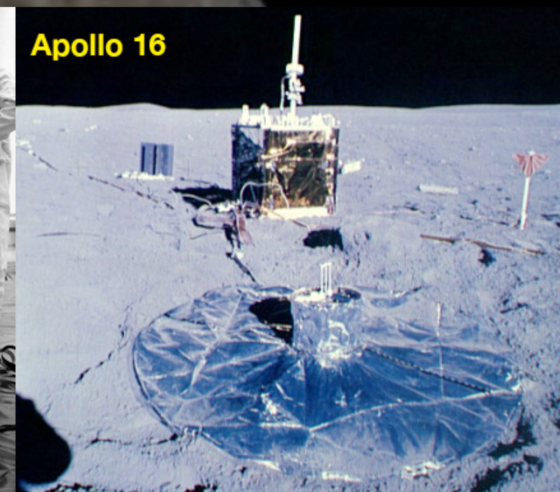
Implications for the Giant Impact hypothesis?

Apollo Seismic Stations

The *complete* Apollo passive seismic network operated from 20 April, 1972, until 30 September, 1977.




Apollo 16 Seismometer Test


Apollo 16

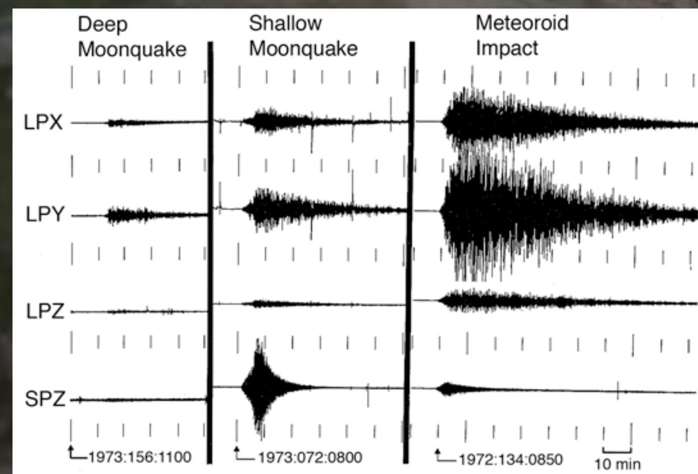
Network too restricted to define global lunar structure

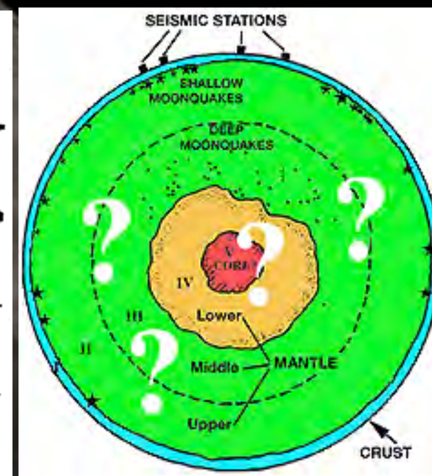

Apollo 11 Geophysics Package deployed on the Moon

Seismology of the Moon

Four types of events induce seismicity on the Moon.

1) **Thermal Moonquakes** - Associated with heating and expansion of the crust. Lowest magnitude of all Moonquakes.





2) **Deep Moonquakes** - 850-1,000 km. > 7,000 recorded. Originate from "nests" - >300 nests defined from Apollo seismic data to date. Small magnitude (< 3). Associated with tidal forces. Predominantly near side.

3) **Meteoroid Impacts** - > 1,700 events representing meteoroid masses between 0.1 and 100 kg were recorded 1969-1977. Smaller impacts were too numerous to count.

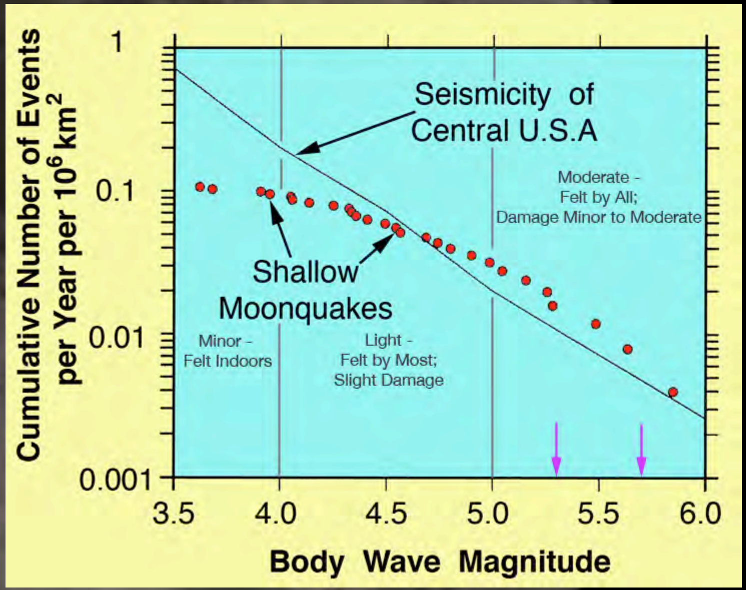
4) **Shallow Moonquakes** - some > 5 magnitude. Exact locations unknown. Indirect evidence suggests focal depths of 50-200 km. May be associated with boundaries between dissimilar surface features. Exact origin unknown.

The Moon Base

The Moon is NOT seismically dead!

Shallow Moonquakes present a potential significant risk to any proposed lunar outpost.

[Oberst & Nakamura, 1992, Lunar Base Workshop, LPI; Oberst & Nakamura (1991) *Icarus* 91, 315-325]



Shallow Moonquake seismicity similar to intraplate seismicity on Earth.

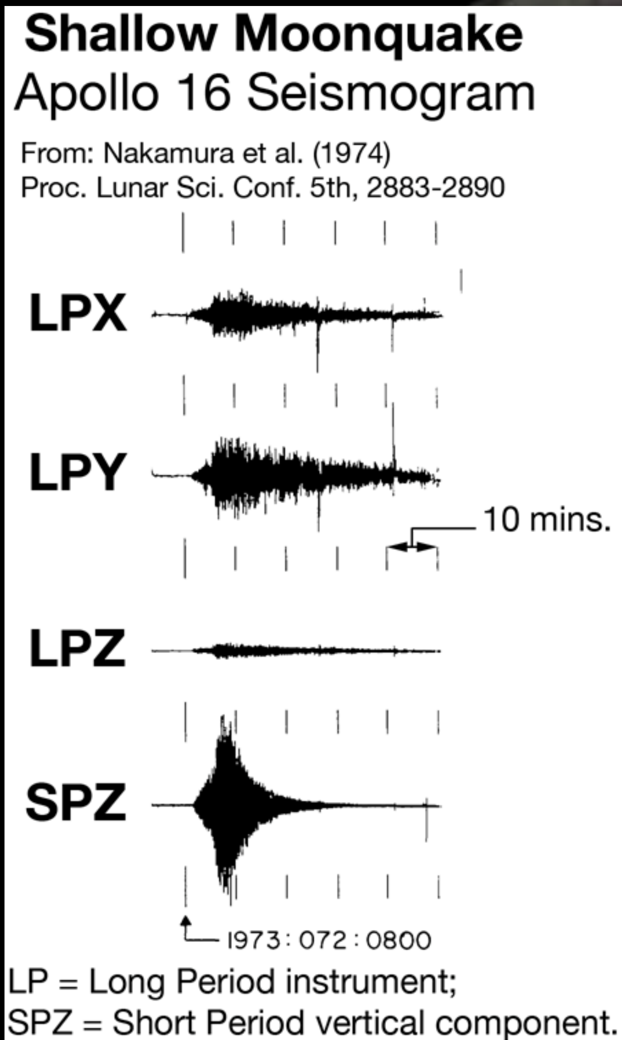
28 **Shallow Moonquakes** recorded, 7 with magnitude > 5.

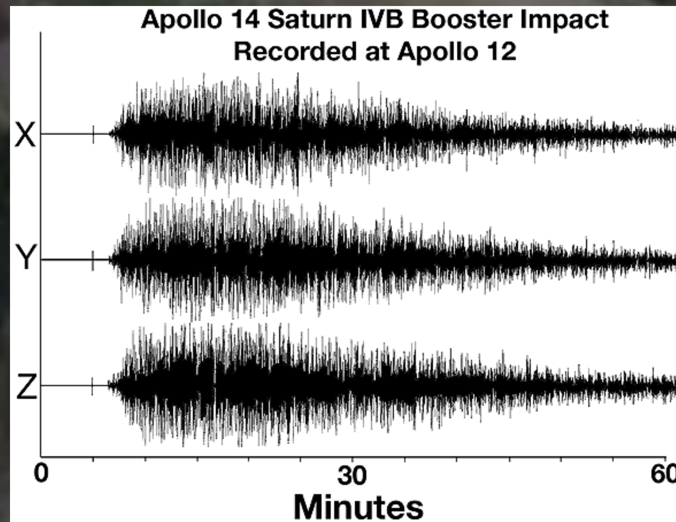
The Moon Base

Examples of Earthquake Damage

Richmond, Utah: 30 Aug. 1962
Duration: 35 seconds.
Magnitude: 5.7

Seismology of the Moon





Dainty et al. (1974)
The Moon 9, 11-29.

Initial build-up phase; Long duration of energy tail off. Highest energy release over a period of 10 minutes or longer.

Lack of chemical alteration allows the Moon to "vibrate" for much longer than the Earth (high Seismic "Q").

Moon seismic Q is approximately an order of magnitude higher than that of Earth.

Ground shakes for a long time!

The Moon is the smallest planetary body in the inner solar system with an old planetary surface.

It’s evolution was halted at an early stage so its structure represents the initial stages of terrestrial planet differentiation.

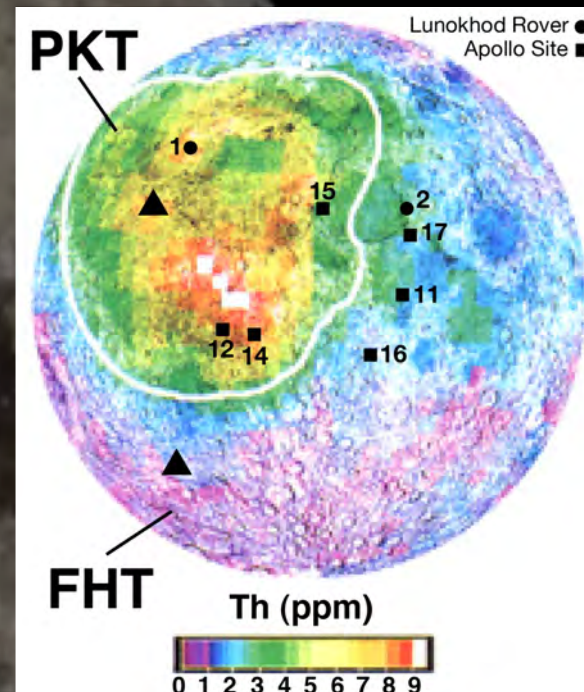
The Moon therefore represents an end-member.

Why Should We Go Back to the Moon?

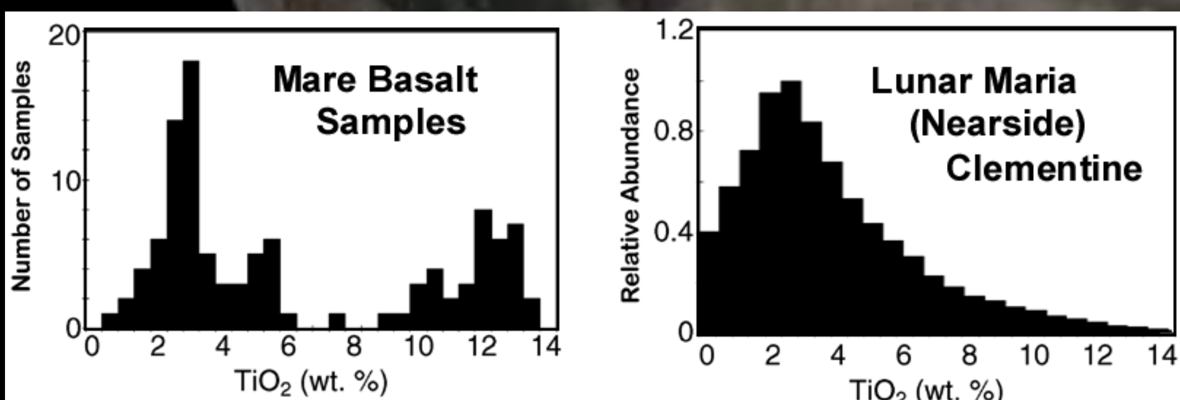
We have <u>NOT</u> "been there-done that"!!

New data show that the Apollo landing sites were not ideal for exploring the Moon.

- Apollo sites close to terrane boundaries;
- Samples contain PKT signature;
- Apollo sample collection is not representative of the lunar compositional diversity (Clementine/ LP and more recent missions) – sample return needed.
- Some lithologies are not present in the sample collection.

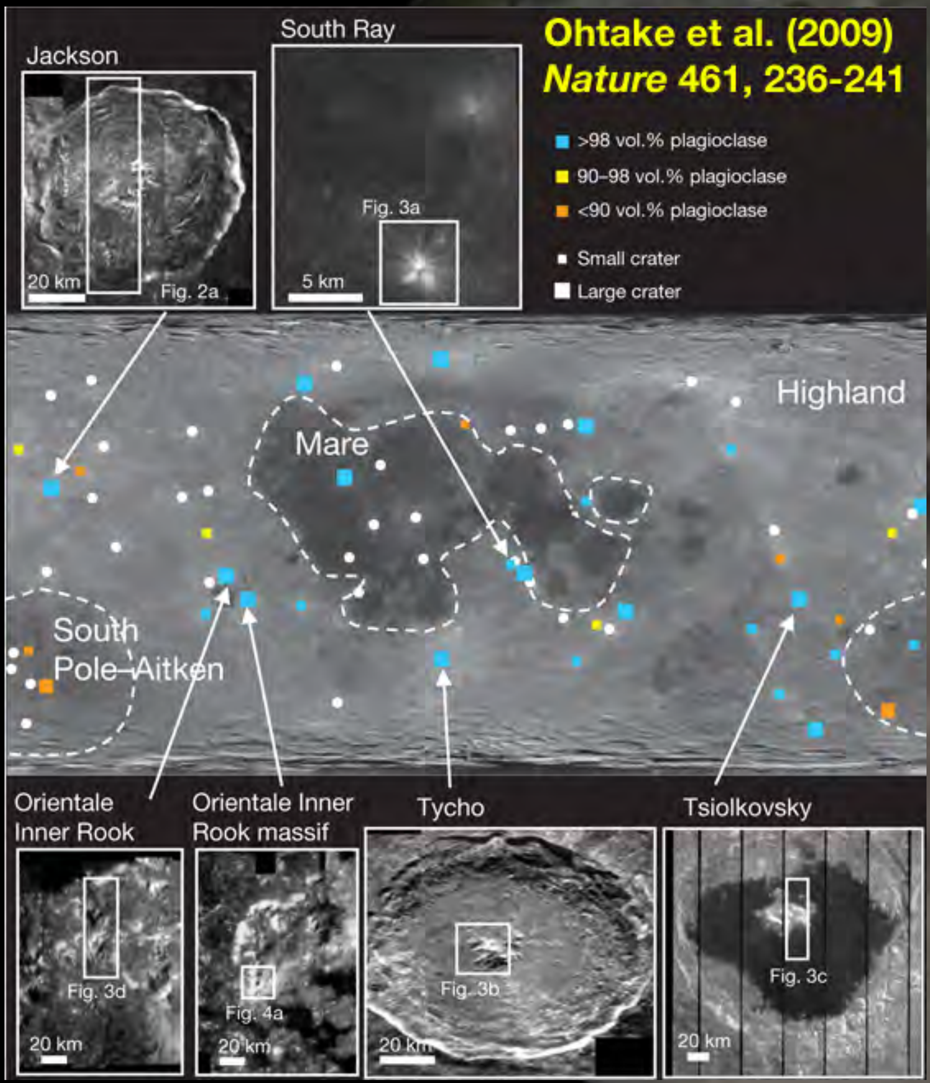


Jolliff et al. (2000) JGR 105, 4197



Giguere et al. (2000) MaPS 35, 193

Recent Mission Results



New Rock Types not represented in the sample collection.

Spinel-rich lithologies: Chandrayaan-1

Pure Anorthosite: Kaguya (SELENE)

Why Should We Go Back to the Moon?

Unresolved Science Questions

Available online at www.sciencedirect.com

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Chemie der Erde 69 (2009) 3–43

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INVITED REVIEW

The Moon 35 years after Apollo: What's left to learn?

Clive R. Neal*

Chair of the Lunar Exploration Analysis Group (LEAG), Department of Civil Engineering and Geological Sciences, University of Notre Dame, Notre Dame, IN 46556, USA

Table 7. Unanswered science questions grouped under themes designed by the Lunar Exploration Analysis Group (LEAG) and the National Research Council of the National Academies

Theme	Science questions
Investigate the geologic evolution of the Moon and other terrestrial bodies.	• What were the initial thermal state and the early thermal evolution of the Moon? • What role did early (i.e., >4 Ga) volcanism play? • What is the composition and depth of origin of the farside and young (i.e., <3 Ga) nearside basalts? • What is the nature of the Moon's global-scale crustal asymmetry, what caused it, and what are the implications for the Moon's internal evolution and present-day distribution of materials? • What is the cause of the center-of-mass/center-of-figure offset? • Is it related to convection and density inversion dynamics, early giant impacts, asymmetric crystallization of the magma ocean, or earth–moon tidal effects? • What is the vertical and lateral structure of the lunar crust and how did it develop? • What is the provenance of the Magnesian Suite rocks? • What is the composition and origin of the lower crust? • What are the characteristics of the lunar core (size, composition), and did the Moon ever support a dynamo-driven magnetic field? What are the origins of lunar paleomagnetism? • Was there a significant late veneer of accretion (post-core formation/early differentiation)? • Are the Apollo geophysical (seismic, heat flow) measurements representative of the whole Moon or are they only valid for the small regions encompassed by the Apollo landing sites? • What is the origin and lateral extent of the 500-km seismic discontinuity? • What is the origin of Shallow Moonquakes (i.e., high-frequency teleseismic events)? • Is there an undifferentiated lower mantle (limited or no involvement in magma ocean melting)? If so, what was its role in lunar magmatism? • Did at least some of the volcanic glasses come from a deep, garnet-bearing region beneath the cumulate mantle? • What was the extent of lunar magma ocean differentiation? • Is the surface distribution of KREEP representative of the underlying crust? • What were the sources and magnitude of heating to drive secondary magmatism? • How was heat transferred from Th, U, K-rich crustal reservoirs to the mantle? What was their role in large-scale crustal insulation? • How are the different suites of plutonic rocks related to specific or localized geologic terranes and to the global geochemical asymmetry? • How is the surface expression of lunar materials related to the Moon's internal structure and evolution (or where exactly do the different rock types come from)?
Quantification of impact processes and histories of the solar system.	• What were the timing and effects of the major basin-forming impacts on lunar crustal stratigraphy? • What is the nature and composition of the South Pole-Aitken Basin, did it penetrate the lunar mantle, and how did it affect early lunar crustal evolution? • What was the impactor flux in the inner Solar System and how has this varied over time? Was there a terminal cataclysm at ~3.9 Ga? • What are the absolute ages of the large rayed craters that are assumed to be Eratosthenian and Copernican in age (e.g., Autolychus, Copernicus, Tycho)? • What are the unequivocal ages of the large multiring basins (i.e., Nectaris, Imbrium, and Orientale)? • Why are there no impact melts older that ~4.2 Ga in the sample collection? Is this a sampling problem or is it because they simply do not exist?
Characterization of regolith and mechanisms of regolith formation and evolution.	• What is(are) the origin(s) of lunar swirls, the light and dark colored "swirl-like" markings up to 100 km across (e.g., Reiner Gamma in Oceanus Procellarum)? • How do the physical/geotechnical properties of the lunar regolith differ between measurement on Earth and in its natural environment on the lunar surface? • How does the process of space weathering occur? • How has the solar wind flux changed over time?
Development and implementation of sample return technologies and protocols.	• What technology development is needed to be able to collect, transport, and curate samples from permanently shadowed regions of the Moon (i.e., samples containing H deposits)? • What technology is currently (commercially) available to aid in (a) robotic and (b) astronaut sampling of lunar lithologies, including contextual information for each sample?

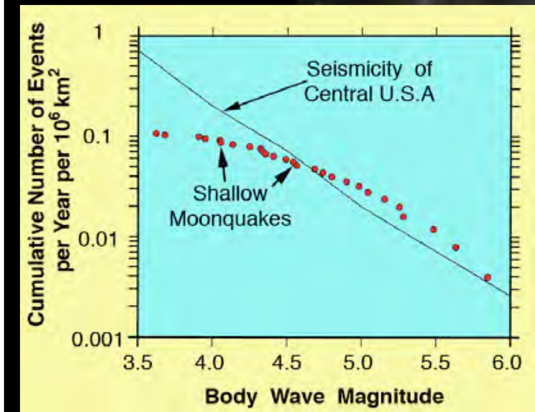
New Views of the Moon (2006) B.L. Jolliff, M.A. Wieczorek, C.K. Shearer, and C.R. Neal, editors, 720 p. Reviews in Mineralogy and Geochemistry, Volume 60. Mineralogical Society of America. ISBN 1529-6466.

Neal C.R. (2009) *The Moon 35 years after Apollo: What's left to be done?* *Chemie der Erde – Geochemistry,* **69**, 3-43 [doi: 10.1016/j.chemer.2008.07.002].

Why Should We Go Back to the Moon?

Unresolved Science Questions

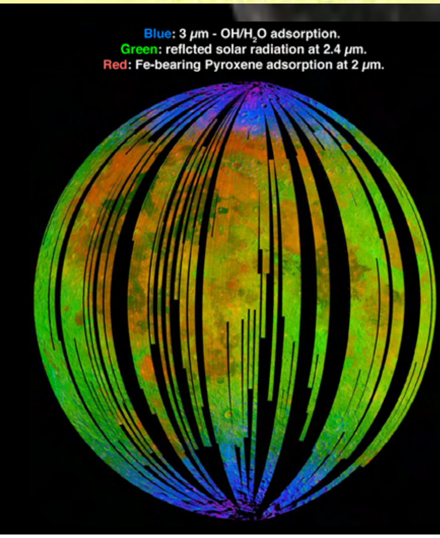
What are the locations and origins of shallow Moonquakes, the largest lunar seismic events?



Oberst & Nakamura (1992) 2nd Conference on Lunar Bases & Space Activities

How does the lunar regolith affect transmission of seismic energy?

What is the effect of seismic shaking in a low gravity environment?



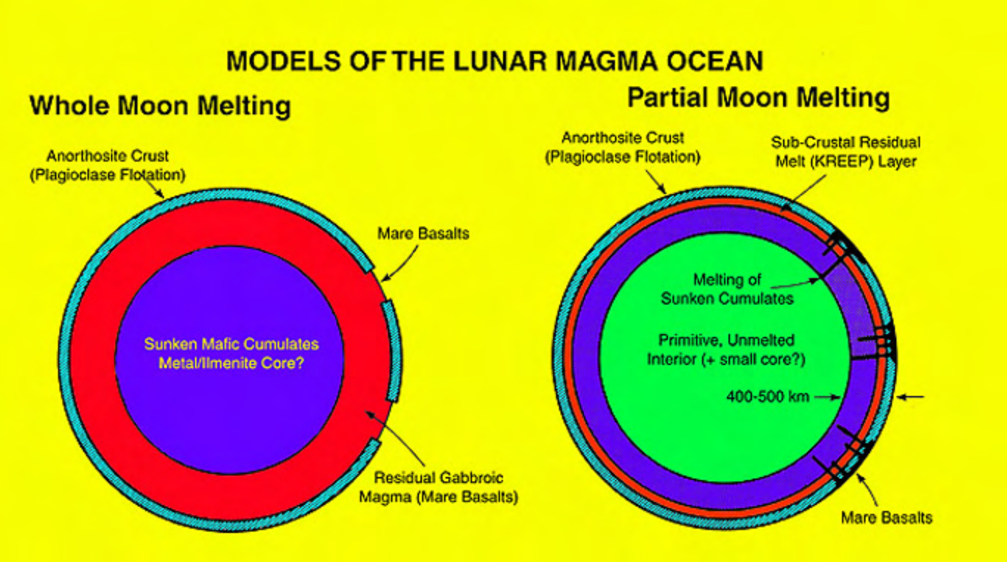
What is the nature of the lunar volatiles in the PSRs? What form are they in and what is their distribution?

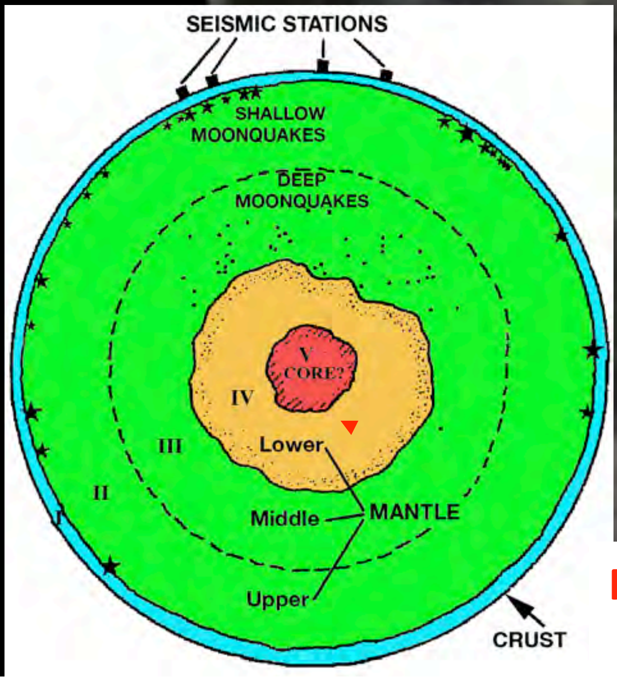
What is the mechanism for the OH/H_2O adsorption around the poles and is this related to the PSR deposits?

Why Should We Go Back to the Moon?

Unresolved Science Questions

If there was a magma ocean, how deep was it?
Is there a Moon-wide ~500 km discontinuity?
What is the nature of the deep lunar interior?





Plastic/liquid zones?

Deep Moonquakes: why so few from the far side?

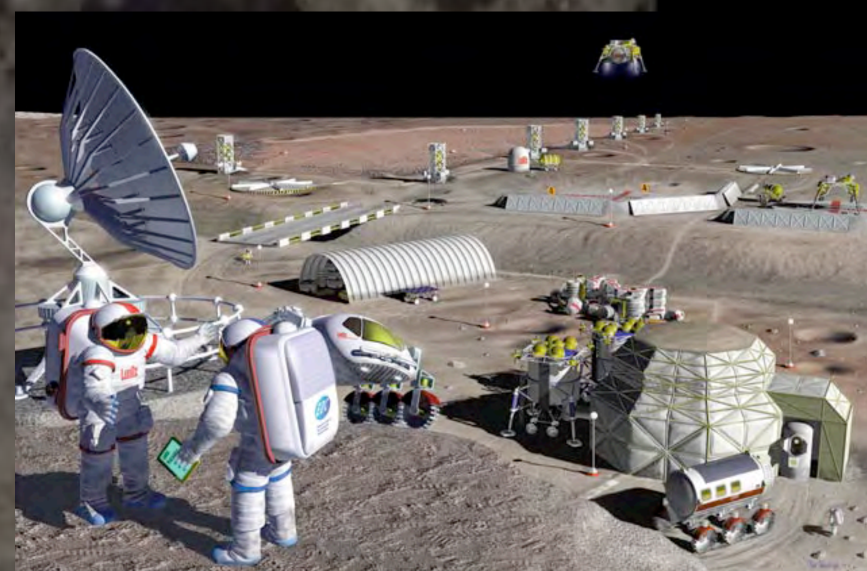
What is the nature of the lunar core? The Moon MAY have a small core ~250 km. MAY be Fe, FeS, but MAY be ilmenite ($FeTiO_3$).

Current models suggest that the core would be solid if Fe metal, but could still be liquid if it was FeS.

Why Should We Go Back to the Moon?

In Situ Resource Utilization (ISRU) is critical for:

- Feed Forward applications;
- Commercial Activity;
- Long-Term Lunar & Solar System Science and Exploration.

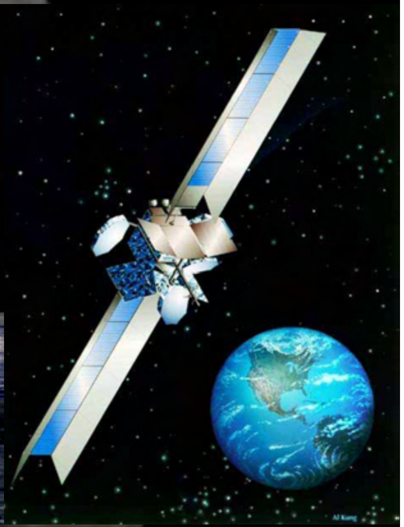


Why Should We Go Back to the Moon?

Expand commercial opportunities and activities.

Commercial Services for Lunar Communications.

- A unique opportunity to provide important infrastructure;
- Significant potential for sale of commercial services to NASA and other customers.

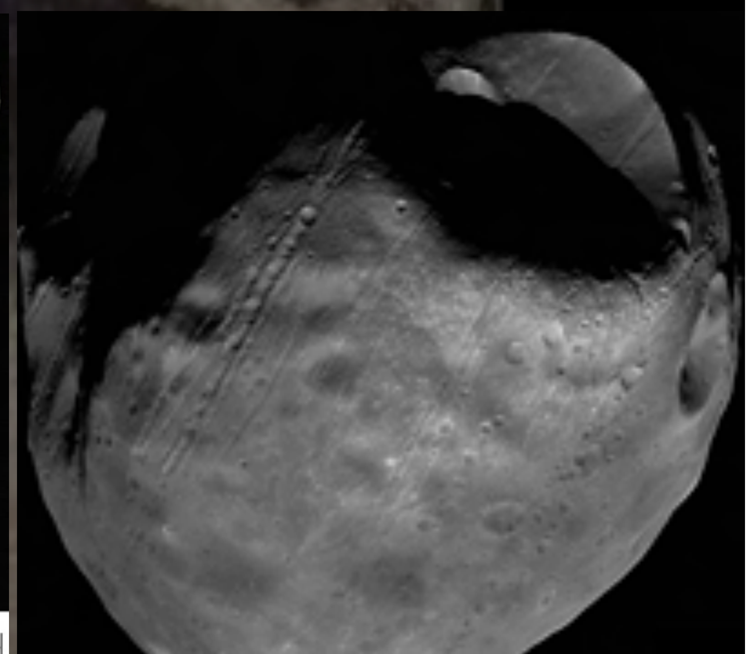


Commercial Services for Refueling depots.

Why Should We Go Back to the Moon?

Feed-Forward to other destinations – Moon as a test bed.

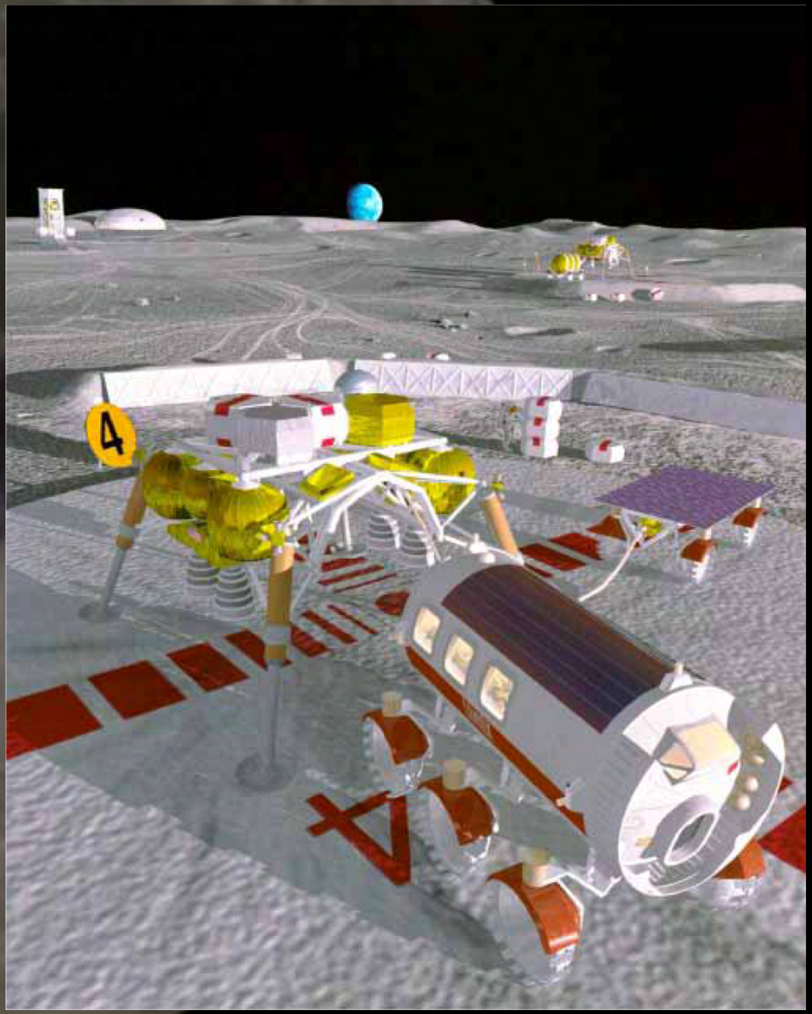
- Moon is close;
- Learn to live and work productively off planet;
- Exit strategy from the Moon is critical;
- Lunar Exploration Roadmap (www.lpi/usra.edu/leag)
  - Science, Feed-Forward, Sustainability Themes



Robotic Precursor Missions

Resource Prospecting and Verification.

- Ground truth is required to validate and characterize the polar and other resources:
  - Determine the form;
  - Measure the amount and location;
  - Characterize the local environment.

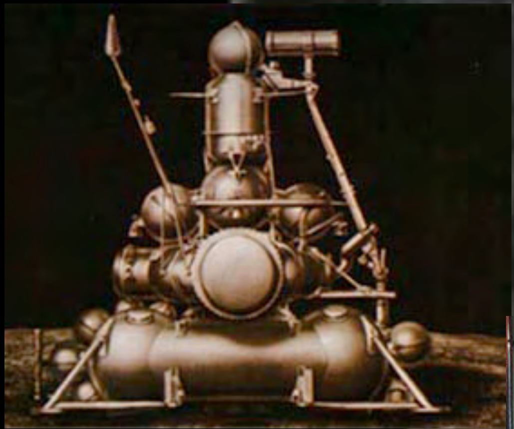


- **The current robotic missions (LRO and LCROSS) are not sufficient.**

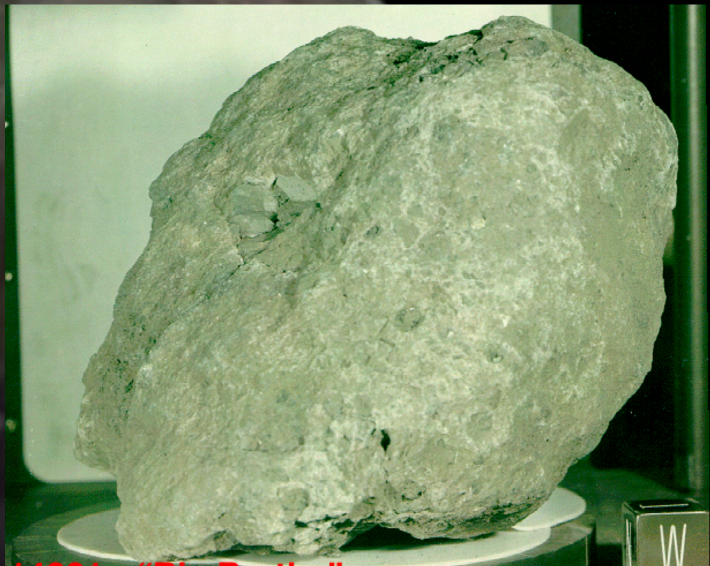
Robotic Precursor Missions

Robotic Sample Return (the gift that keeps on giving).

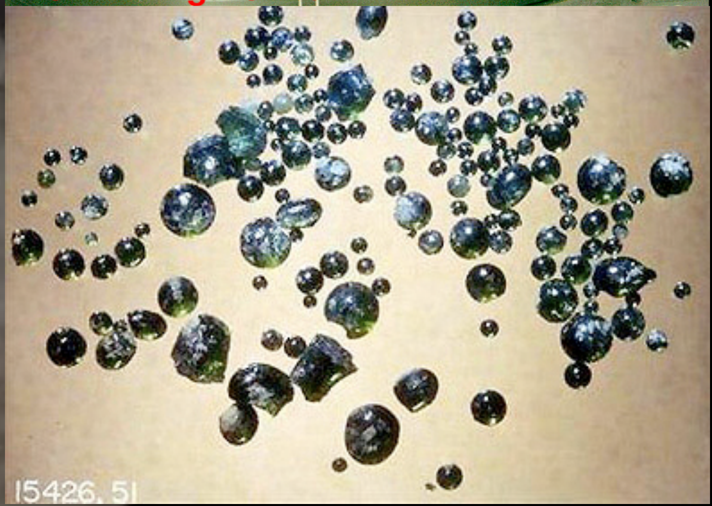
- Important for science and exploration (new lithologies and potential resources);
- Enabling technology for other destinations.



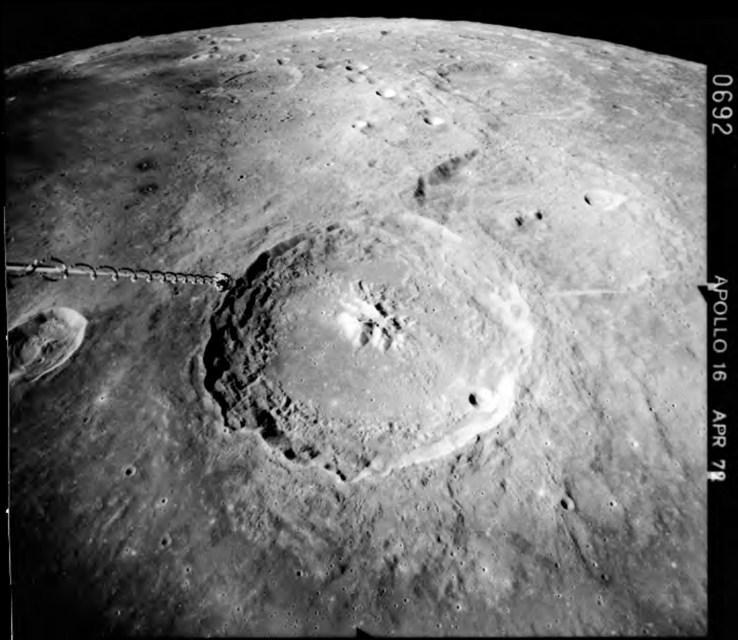
Soviet Technology

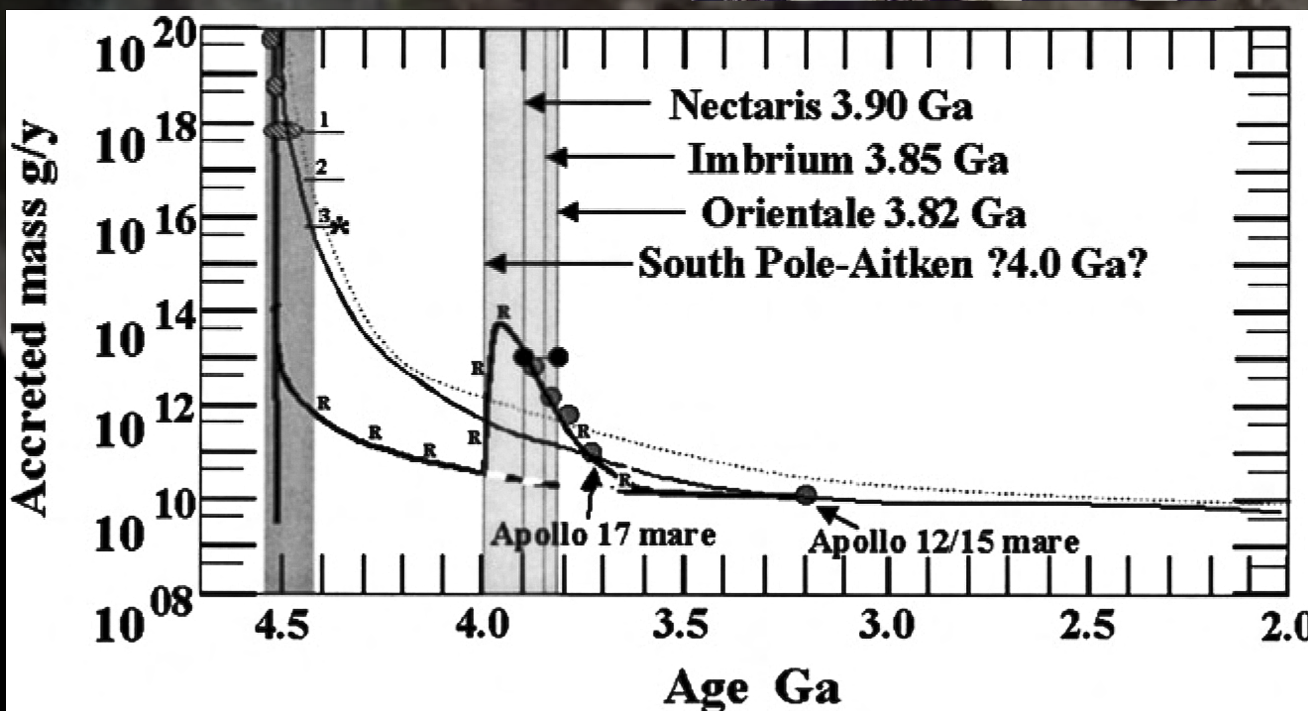


14321 - "Big Bertha"



Impact Chronology





Summary

The Moon represents the "Rosetta Stone" for the science & exploration of the Inner Solar System:

- Preserves the earliest stages of planetary differentiation;
- Preserves the early bombardment history of the inner solar system;
- It is the type locality for understanding the space weathering of airless bodies.

New missions always produce new discoveries that require revision of previously formulated hypotheses.

Important Solar System science questions remain that can be addressed by new missions to and data from the Moon.

Summary

The Moon is an Exploration Asset:

- Technology Development (robotic & human science and exploration);
- Protection technologies for human missions;
- Systems Integration for human missions.